5-2008

Lithologic and structural control on the evolution of a knickzone on the James River, central Virginia Piedmont

Karl Lang
College of William and Mary

Lithologic and structural control on the evolution of a knickzone on the James River, central Virginia Piedmont

An honors thesis submitted in partial fulfillment of the
requirements for the degree of Bachelor of Science in Geology
from the College of William and Mary in Virginia,

by

Karl Alexander Lang

Accepted for ___________________________

Dr. Greg Hancock _________________________

Dr. Chuck Bailey _________________________

Dr. Brent Owens ___________________________

Dr. Sarah Stafford ___________________________

Williamsburg, Virginia
April, 2008

Table of Contents

List of Figures

Abstract

Recent mapping of a broad 5 kilometer (km) knickzone located ~130km upstream of the Richmond Fall Zone on the James River, central Virginia Piedmont, indicates the mechanism of incision and knickzone creation is largely controlled by the underlying bedrock. This current hypothesis was determined through detailed analysis of reconstructed terrace profiles, field mapping and surveying, and past ^{10}Be cosmogenic radionuclide dating. Nearly all current data supports the hypothesis that the knickzone has been largely stationary during the last 1 Ma, though it is possible that the river has experienced multiple migratory knickzones during this time. This research project works to further these earlier efforts by focusing on how certain lithologic and structural characteristics maintain a dominant control on knickzone placement and orientation. Precise surveying of the river surface throughout the knickzone is used to construct detailed longitudinal profiles that are correlated with lithologic and structural data. Evidence is also drawn from the construction of a 1:12,000 scale bedrock and surficial geologic map of the study area, analysis of longitudinal and cross valley profiles of the main channel and tributaries (created from 1: 24,000 scale topographic maps) in combination with analysis of aerial photographs of the study area, channel flow direction in tributaries and site specific field observations. Future plans involve constraining rates of incision within the knickzone using ^{10}Be cosmogenic radionuclide dating techniques to date terrace deposits. Terraces several kilometers up and down stream of the knickzone have already been dated. A detailed interpretation of the James River knickzone will be helpful in determining the extent of landscape disequilibrium in the piedmont, and further hypothesizing the mechanism for this disequilibrium.

Abstract (AGU)

The longitudinal profile of the James River within the central Virginia Piedmont displays a significant change in convexity that may be evidence of landscape disequilibrium. Approximately 130 km upstream of the Richmond Fall Zone, this change in convexity is expressed as a broad 5km knickzone with an average gradient of 1.8m/km. Knickzone incision has created multiple terrace levels on both banks of the river, which have been confirmed by hypsometric evaluation of the river valley using DEM, soil and field analyses. In this area, the James River streambed is bedrock dominated, with significant outcroppings above water levels. The rocks are mostly meta-sedimentary and metavolcanics including a complexly deformed mélange zone. Field mapping of a 50 km^2 rectangle including the knickzone has allowed for the construction for surficial and bedrock geologic maps at the 12,000 scale. Longitudinal profile analyses of the James River and major tributaries have been created from 24,000 scale topographic quadrangles and confirmed with field surveys. ^{10}Be cosmogenic radionuclide dating on sand or cobbles from terraces will provide minimum estimates of terrace abandonment ages and an estimate of incision rates. Previous research on terraces up and downstream of the knickzone revealed CRN dates of roughly 1 Ma and incision rates on the order or 55m/Ma. A complete data set should allow for a more accurate account of whether knickpoint migration is occurring, a possible mechanism of migration, and the rate and timing of knickzone incision, in an effort to reconstruct the landscape evolution.

Introduction

This project investigates a pronounced convexity in the longitudinal profile of the James River as it flows through the central Virginia Piedmont. Bound to the west by the Blue Ridge Mountains and to the east by the Coastal Plain, the Piedmont may be thought of as an intermediary province, characterized by extensive drainage networks that drain the Blue Ridge and deposit sediment on the Coastal Plain. This province is physically identifiable by its low relief uplands and sweeping meandering stream channels. Current researchers believe that many of these channel networks are in a state of landscape disequilibrium (Hancock and Harbor, 2002). This particular setting is ideal for studying long term geomorphic changes, as it is tectonically quiescent are along a passive continental margin.

Recently, an increasing body of research has indicated that the Piedmont is a disequilibrium landscape. Evidence for this disequilibrium is best exhibited in the generation of relief formed as streams crossing the Piedmont incise at a rate greater that regional landscape denudation. While this is directly evidence within the Piedmont it may also be occurring across the eastern seaboard. Based on regolith production rates observed to have a residence time ~1Ma, Pavich (1989) first identified upland, or interfluve, lowering rates to be on the order of 4-20m/Ma. Comparatively, Felis (2003) found stream incision rates along the James River to be 35-60 m/Ma. These results were calculated using ^{10}Be cosmogenic radionuclide dating of successive terraces encompassing the study area for this research project. As well, Hancock and Harbor (2002) used similar techniques to measure stream incision rates around 45m/Ma based on fluvial terraces dating back the last ~1 Ma. Further north, Reusser *et al*. (2004) identified extremely rapid incision rates along the Potomac and Susquehanna rivers of up to 600-800 m/Ma also using ^{10}Be. These extreme incision rates pertain to episodic pulses of incision beginning 35 ka and ending 13-14 ka (Reusser *et al*., 2004). Importantly, there is a temporal scale to river incision. On a million year time scale, incision rates reflect those observed by Hancock and Harbor (2002). However, as Reusser *et al*. (2004) observed shorter term variability may result in rates 10 to 20 times the long term average.

Contrary to this view of landscape disequilibrium is one of dynamic equilibrium, first proposed by Hack (1960). Hack looked at regions in the southern Appalachians, noticing that these areas maintained a high degree of relief despite draining to a common base level. His explanation for the relief was through differential rock erosion. Rocks harder to erode would form high slopes under a constant erosion rate. If we apply this viewpoint to the Piedmont we must assume a constant rate of denudation. Because channel and interfluve erosion rates are equal, as the landscape continues to evolve no new relief is generated, but rocks of harder lithology maintain steeper slopes. The large record of variable incision evident in the aforementioned research implies variability in erosion rates between channels and the general landscape. Thus, this work does not directly support the idea of a dynamic equilibrium.

A stream channel in equilibrium, or a graded channel, maintains a consistently concave longitudinal profile following an exponential form (Pazzaglia and Gardner, 1998). In contrast, the longitudinal profile of a stream in disequilibrium is variable. Typically disequilibrium is characterized by subtle convexities called knickzones or knickpoints (figure 1). A knickzone is simply a longer or lower sloping, perhaps less obvious knickpoint. These knickzones are perhaps the most important mechanism by which a stream is able to readjust its longitudinal profile, and evolve (Pazzaglia *et al*. 1998). However, disequilibrium landscapes may also generate stationary knickzones dependent on differential lithology or structural features that resist erosion.

As knickzones control the evolution of a channel, they are also controlled by certain elements of channel bottom. Channel incision is related to the stream power of a river, or the ability of that river to erode its bottom (Whipple, 2004). This is expressed in the following equation:

$$\omega = \frac{\rho g Q S}{w}$$

Where the stream power per unit width (ω) is equal to the product of the density of water (ρ), gravity (*g*), discharge (*Q*), and channel slope (*S*) divded by the channel width (*w*) (Howard and Kirby, 1983). The erosivity of a stream has been suggested to be proportional to the stream power per unit length of the bed, thus:

$$-\frac{\partial z}{\partial t} = k(QS)^n$$

Where the change in elevation with respect to time (erosion rate) is equal to the discharge slope product (*QS*) from the stream power equation multiplied by an empirical constant of erosivity *k*, and raised to another constant *n*. Note that this is more commonly expressed as:

$$-\frac{\partial z}{\partial t} = kA^m S^n$$

Where the discharge is proxied by the area (*A*) raised to empirical exponents *m* and *n* that account for variability in erosional processes (Howard and Kerby, 1983). These values vary between 0.3 and 1.0. (Howard and Kirby, 1983; Pazzaglia *et al*., 1998; Tucker and Bras, 2000; Whipple and Tucker, 1999).

Taking these equations to represent the incision characteristics of a particular stream reach, we understand that as the empirical constants vary, so will the stream power. Regional differences in incision along a channels longitudinal profile create the convexities known as knickzones. Here we can differentiate between two types of knickzones; knickzones with high slopes driven by high erosion rates, and knickzones with high slopes governed by a low k value (resistent bedrock), termed migratory and stationary knickzones respectively.

Migratory knickzones move upstream with time. It is easy to think of migratory incision as maintaining vertical and horizontal incision components. As a migratory knickzone incises down, it is also eroding upstream. This may be accomplished by a variety of mechanisms, illustrated by Selby (1985), such as undercutting, relaxation, rotation, or some possible combination. As these knickzones migrate upstream with time, they may leave an incision history recorded in fluvial terrace deposits alongside the channel. These terraces, when mapped and reconstructed show an upstream migration pattern of the knickzone. If dated, terraces generated by migratory knickzones will also show a decrease in age upstream. These mechanisms are dependent on the underlying geology to some extent, but they are not dominantly controlled by the lithology or structure. That is to say the bedrock geology may effect the mechanism of erosion, but it does not control the placement or movement of the knickzone (figure 2, A).

Conversely, stationary knickzones are dominantly controlled by lithologic or structural characteristics. They do not migrate upstream with time, and a reconstruction of terrace profiles would mimic the modern longitudinal profile with terrace ages ranging upstream and downstream of the knickzone (figure 2, B). Commonly these knickzones are created due to the presence of a differentially harder lithology in the channel bottom. They may also be created and maintained by structural features that inhibit incision locally. Since a rock is harder to erode, to achieve equilibrium a higher stream power is needed to maintain a constant erosion rate along its profile (this may be accomplished by increasing channel slope) (Whipple 2004). This explains the longitudinal profile convexities that maintain their location determined by the extent of a differentially harder lithology (Pazzaglia *et al*., 1998).

Felis (2003) called the current study area a stationary knickzone. This conclusion was based on the cosmogenic dates he calculated on terraces upstream and downstream of the knickzone. A preliminary estimation, he attributed the cause of the knickzone to a band of mélange crossing the James at its toe. Dunford-Jackson (1975) identified stationary knickzones occurring along the Rappahannock River, north of the James. Using relative dating techniques and careful mapping, he reconstructed terrace profiles indicative of stationary knickzones. These correlated to lithologic contacts between metasedimentary rocks, Mesozoic basin conglomerates and a northern extension of the same mélange crossing the James in this area. Interestingly he maintained that some of these knickzones may be due to past incidence of stream capture or piracy. This would suddenly increase discharge, and thus stream power and erosivity, eroding the river bottom at a substantially higher rate. It is hard to image, however how such a knickzone could be maintained in a stationary position.

Migratory knickzones have also been recognized in the Piedmont at a number of locations. Dunford-Jackson (1975) identified several migratory knickzones along the Rappahannock longitudinal profile. Additionally, Harbor *et al*. (2005) identified migratory knickzones along the Maury River profile (a tributary to the James River) in their study as well as Reusser *et al*. (2004) in the Potomac and Susquehanna Rivers and Pazzaglia and Gardner (1998) in several mid Atlantic Piedmont river systems. Frankle *et al*. (2007) were able to experimentally reproduce and characterize migratory knickzones in a vertically bedded substrate in a successional flume experiment designed to mimic observed conditions within the mid-Atlantic Piedmont.

It is important to distinguish here between lithologic or structural control on a knickzone and control on a particular reach of stream. Richardson and Carling (2005) identified the difference between a hydrodynamically controlled channel and a structurally controlled channel. A hydrodynamically controlled channel is one dominantly controlled by its flow. These channels are characterized by certain bedrock erosion mechanisms, namely abrasion and corrosion, and exhibit bedforms dependent on their unique flow conditions. A structurally controlled channel experiences bedrock erosion mechanisms determined by its structural characteristics, like plucking. These channels are typically obviously controlled by local structure in that they distinctly follow a preferred direction controlled by fracturing, faulting or lithologic changes. A reach may be structurally controlled, but not a stationary knickzone. Importantly, a stationary knickzone only occurs when the channel bottom steepens in an attempt to maintain a consistent erosion rate by increasing its stream power within an erosion resistant area. It is entirely possible that a migratory knickzone passes through a structurally controlled area, or that a hydrodynamically controlled reach occurs within a massive unit comprising a stationary knickzone by differential lithology. These terms are closely correlated, but not always causative.

Disequilibrium, as evidenced by migratory knickzones, may be driven by a number of larger spatial and temporal scale mechanisms. Base level change through eustatic sea level drop, and sediment or discharge variance as a result of climatic changes are commonly cited as causal mechanisms for migration. Figure 2A illustrates the steepening, and subsequent migratory knickzone due to base level drop. Pazzaglia and Gardner (1994) identified isostatic uplift as another explanation for disequilibrium in the Piedmont. They modeled sediment onloading of the Coastal Plain, with the Fall Zone acting as a lever fulcrum to uplift the Piedmont, and concluded that the Piedmont has experienced 35-130m of uplift within the last 15 Ma; not enough to completely account for the currently observed rates of incision, but enough to contribute. Reusser (2004) suggested a similar mechanism corresponding to uplift of the glacial forebulge for streams with glaciated catchments.

Climatic changes are also viable mechanisms for causing disequilibrium by influencing stream discharge, sediment load and catchment reorganization with increased precipitation, storminess, and eustatic sea level. Sea level alone may generate migratory knickzones through base level drop (figure 2A) and has varied up to 150 m over the last 15 Ma (Haq, 1987). Sklar and Dietrich (1998) documented the contribution of sediment supply to stream power and channel erosivity, noting that the slope dependence of stream channels on maintaining a bedrock versus alluvial dominated bottom can either induce or protect bedrock erosion. Felis (2003), Dunford-Jackson (1967) and Reusser *et al*. (2004) have all cited this mechanism as a contribution to profile readjustment within their respective study areas, all drawing linkages to late Pleistocene climate fluctuations, except Dunford-Jackson (1967) who accounted for variation dating back to the Cretaceous.

We focused on a pronounced knickzone along the James River previously investigated by Felis (2003). He noted that along this knickzone reach are both a visible terrace succession and variable bedrock lithologies. Here, the James River is a mixed bedrock and alluvial meandering river that flows over 350 km from its headwaters in the Appalachian Mountains to its mouth of the Chesapeake Bay. Its longitudinal profile shows several significant convexities along its length including: a point located along the Fall Zone; a point 135 km upstream; and a point located 220 km upstream near Lynchburg, Virginia before the James reaches the Blue Ridge Mountains (figure 1).

We focus on a study area of ~50 km^2 surrounding the second pronounced knickzone along the James River longitudinal profile (figure 3). Here the James River forms the county border, separating Buckingham County to the south and Fluvanna County to the north. The knickzone is approximately five km in length dropping nine meters, for a gradient of 1.6 m/km. This slope is three to four times the average gradient both upstream and downstream of this reach. Within this reach the river morphology changes from a sinuous meandering channel to anabranching, with elongate vegetated alluvial islands. This change in morphology occurs in other areas along the James, however these occurrences are infrequent. Since river morphology is directly correlated to channel slope, discharge and sediment throughput (Schumm, 1977), these alluvial deposits may reflect small slope changes within the channel that are too small to be observed using topographic maps alone for analysis.

Felis (2003) noted the presence of fluvial terraces lining the river within the study area at various elevations, even mapping some to the north of the river. Felis (2003) was able to obtain strath elevations for some of these deposits, indicating that at least some of the incision within the reach has been directly into bedrock. If there are more strath terraces within the region, for example along the southern bank, then they may also be mapped along the perimeter of their strath. Since this region is noted for its poor bedrock exposure, it is also possible to estimate strath elevations as they exhibit a sharp break in slope that would correspond to the top of eroded bedrock.

The James River flows over at least three distinct lithologic units within the study area, characterized by greenschist grade metamorphism and complex deformation. In this region, mesoscale folding is ubiquitous, however larger scale structure is difficult to discern beyond the general subvertical foliation.. Early bedrock interpretations of this region consist of work conducted by Smith *et al*. (1964) in Fluvanna Country (north bank of the James) and Brown (1969) of the Dillwyn quadrangle (south bank), both at 1: 62,500 scale identified the basic lithologies of the rocks underlying the James (figure 4A, 4B). A solid understanding of the bedrock units intersecting the channel is necessary to determine if there is a lithologic or structural influence on this knickzone. Most importantly however, is discerning a structural of litholgic differences between the units that might have a differential effect on bedrock erosion within the channel.

Historically, the differences between units in this area that might have a hydromorphic influence have been debated. Smith *et al*. (1964) identified rocks in the western part of the study area that include muscovite-paragonite and chlorite-muscovite-paragonite phyllites which they termed the Evington Group, and inferred to be early

Paleozoic in age by stratigraphic correlation. These were subdivided stratigraphically to the upper, middle, and lower paragonite units each 1,200, 500 and 1,500 meters thick. They called these rocks metamorphosed greywackes, subgreywackes, quartzose phyllites and argillites and quartzites with a felsic to mafic volcanic provenance. In northeast striking contact to the east of the Evington Group, located at the very base of the knickzone are metamorphosed volcanic and sedimentary rocks 900-1800 meters thick. This unit contains a metamorphosed porphyritic quartz-feldspar rock identified as "aporhyolite" as well as very fine grained quartzite and phyllite as well as amphibole schists and gneisses, biotite and chlorite schist and other metamorphosed intermediate igneous rocks. Approximately 3.5 km downstream in the channel, the metavolcanic unit contacts the Arvonia Formation, a unit containing slate, quartzite and oolitic chlorite-garnet schist. Greenstone was mapped as elongate cross cutting bodies striking northeast throughout the study area, as were Triassic diabase dikes that are northeast and northwest striking (Smith *et al*., 1964).

Brown (1969) identified lithologies in the western part of our study area as dominantly metamorphosed arkoses, chlorite-quartz-muscovite schists and phyllites. These metamorphic rocks locally contain clasts and pebbles, so he named the rocks a metagreywacke which he determined to be ~4,000 ft thick. These metasedimentary rocks also include metadiorite and ultramafic blocks in their complexly deformed structure. Brown (1969) essentially combined the two units originally identified by Smith *et al* .(1964) as the Evington Group and the metasedimentary with metavolcanics because he identified no apparent separation between them, and proposed that they were of the same volcanic provenance. For these combined units, Brown tentatively continued to use the term Evington group (?) [sic]. He identified the same contact with the Arvonia Formation, and used the relative relation to say that the Evington Group (?) was early Paleozoic in age. He also maped similar diabase dikes in a northwest and northeast striking orientation.

These studies mention several areas of interest in regards to river morphology. There are possible boundaries of differential lithologic hardness found along contacts. Two prominent areas exist between the eastern metavolcanic and western metasediments identified by both authors between the same metavolcanics and the slate belt. The blocks identified by Brown (1969) may correspond to differential hardness boundaries within an individual unit. The greenstone and diabase units mapped by both authors may also correspond to boundaries cross cutting multiple units.

The interpretations by Brown (1969) and Smith *et al*. (1964) set the stage for a few later revisions that focus on one unit in particular, the metasedimentary rocks containing allochthonous blocks first identified by Brown (1969). These studies are particularly important because the eastern contact between this unit and the metavolcanic unit is in direct correlation with the toe of the knickzone. Brown (1986) focused exclusively on this portion of the study area around Shores, Virginia in a field trip guide. This guide investigated what was later termed as the "Shores Complex," previously interpreted by Brown (1969) to be part of the Evington Group, and containing a high proportion of greenstone and other metavolcanic rocks. Later, Pavlides (1989) used these rocks' distinct magnetic anomaly striking to the northeast into northern Virginia, to group and rename them the Mine Run Complex. Brown (1986) reinterpreted this area as an intensely deformed metasedimentary belt locally containing mélange. These mélange units are particularly discernable along the James River near Shores. Now defined as a large scale metamorphosed and complexly deformed unit with a largely metagreywacke matrix, the unit contains allochthonous blocks of greenstone, ultramafic and felsic intrusive igneous rocks which are all inferred to be differentially harder than the matrix. Brown used a Rb/Sr whole rock isochron date of 440 +/- 8 Ma obtained by Pavlides *et al*. (1982) for an unmetamorphosed intrusive monzonitic pluton that disrupts the Shore lineation 50 km northeast of Shores to constrain the age of deformation of the Shores Complex. Here Brown also takes the view that the Shores complex may have the geometry of a wedge, bounded by faults that was first suggested by Evans (1984).

The 1993 State Geologic map of Virginia supports this mélange interpretation, which at 1:500,000 scale identifies four units within the mapping area, the first being an early Cambrian metagreywacke with quartzose schist locally containing metagabbroic blocks (figure 4C). The units are reported to become more tectonized moving east to west, with near mylonitic schists resulting in the western portion where it lies in eastern contact with the Mine Run Complex, zone III as identified by Pavlides (1989). This is a mélange including blocks of amphibolite, mafic and ultramafic igneous rocks, serpentine and talc with a metasedimentary phyllitic to schistose matrix. This unit can be distinguished from the aforementioned metagreywacke due to its distinctive magnetic signature. East of the mélange is the Ordovician Chopawamsic Formation of intertonguing felsic to mafic metavolcanics, quartzite, metagreywacke and schist. The Chopawamsic Formation continues to the east where it contacts the previously identified Ordovician Arvonia Formation. There is a thin portion of the Arvonia within the study area in a remnant synform. The Arvonia Formation is identified to be slate and porphyroblastic schist in this area. The age of this formation is based on longstanding paleontologic data.

Also of hydromorphic interest in this area is the relative structure of these rocks. Richardson and Carling (2005) identified the ability of bedrock structural features to maintain a morphologic control on streams, so it is nessecary to account for structure in an analysis of the knickzone. Smith *et al*. (1964) defined the general structure in the study area as east dipping foliation, typically parallel to bedding surfaces. There is subvertical foliation around the reach of Big Island, in the center of the study area, and west dipping beds thereafter to the east (see figure 3). They mapped an overturned anticline crossing the study area just before the confluence of the Hardware River, termed the Hardware Anticline. This is based largely on overturned bedding observed in outcrops along the Hardware River within the study area and one other location within the county. A tight syncline is oriented parallel to the metavolcanic and Arvonia slate contact is termed the Long Island Syncline. They do not identify much fracture data within this region. Additionally, the biotite and megascopic phyllosilicate isograds are mapped in the eastern part of the study area, trending northeast with foliation and the Hardware Anticline.

Brown's (1969) structural interpretation is very similar to that of Smith *et al*. (1964). He identified east dipping foliation parallel to bedding with two small antiform and synform structures crossing the River around Seven Islands and Big Island (identified in figure 3). Brown included the overturned Hardware anticline with only a few sites of overturned bedding along the Hardware River. Additionally, Brown interpreted the Long Island Syncline to be overturned.

Evans (1984) deviated from these previous interpretations, adding that the western metagreywacke unit or “Hardware metagreywacke” is separated from the adjacent phyllitic rocks by the Buck Island Fault, a northeast striking thrust fault located west of Scottsville and out of the study area. This Hardware metagreywacke is then overthrust by the Shores Complex which is in turn overthrust by the Chopawamsic Formation in a series of large scale faults within all units. Pavlides (1989) identified a similar fault, which he termed the Mountain Run fault to distinguish the metagreywacke from the Mine Run Complex (Zone III within the study area). This new terminology originated when the unit was found to have a distinctive magnetic signature that followed a northeast striking trend into northern Virginia.

It is apparent that there is the potential for both structural and lithologic controls on streams in this area. The question remains however, if this control extends to the James River channel to the ~5 km knickzone within it. The lithologic and structural diversity within this area makes this question detailed and complex; and this requires a structured and disciplined approach in its analysis. More specifically, based on our findings we hope to answer the following questions about this study area:

1. Is this in fact a stationary knickzone or a migratory knickzone?
2. How does incision occur within the knickzone?
3. Is this reach structurally or hydrodynamically controlled?
4. Is this knickzone evidence of landscape disequilibrium, and what is the most likely causal mechanism?

Methods

Work for the project can be divided into three categories including an initial mapping phase, subsequent detailed surveying, and laboratory analyses of topographic maps, aerial photos and the accumulated field data. Mapping of the ~50 km^2 study area, with a primary focus on the tributaries and the main channel itself was conducted during the summer of 2007 from June to August, and then periodically throughout the 2007 and 2008 academic year. Mapping was intended to help determine to what extent the knickzone was structurally or lithologically controlled. Low water surface surveying of the toe of the knickzone was completed in two trips representing two transects of the knickzone, the first during November 2007, and the second during March 2008. Surveying allowed for the construction of a more detailed longitudinal profile of the knickzone than could be created from 1: 24,000 scale topographic maps or 30 m Digital Elevation Models. Further laboratory analysis began with longitudinal and cross valley profile constructions from 1:24,000 topographic maps over the summer and continued with increasing focus throughout the 2007-2008 academic year.

Field mapping

Mapping is nessecary to answer the first research question. While there is already a significant amount of research regarding the bedrock in the study area, all of this work has been completed on a scale too small to identify all of the lithologic or structural nuances that may be controlling the placement of the knickzone. We conducted 1:12,000 scale bedrock and surficial mapping of the ~50km^2 study area paying particular attention to areas surrounding the main channel and its tributaries. Bedrock mapping focused on the differences between structure and lithology within units that might account for the placement of the knickzone. Surficial mapping, conducted by Lauren Parker focused on increasing strath elevation data (begun by Felis (2003)) to reconstruct past longitudinal profiles as a means to determine the evolution of the channel.

Summer mapping was conducted alongside a fellow student and collaborator Lauren Parker and advisor Dr. Greg Hancock (figure 5B). Lauren Parker took responsibility for mapping the extent and depth of surficial deposits consisting entirely of terrace deposits and modern floodplain extents. This included deposits for both the main channel and tributaries. The author took responsibility for bedrock mapping.

Bedrock mapping included the delineation and mapping of contacts, and general structure of bedrock cropping out within the roughly 50 km^2 area surrounding the knickzone reach. As mapping was primarily conducted during the summer, both vegetative overgrowth and bedrock saprolitization was a continuous problem. Saprolite is ubiquitous in upland exposures, of which there are generally very few. For these reasons outcrop is limited to lowland areas, dominantly within the main channel and tributaries themselves. On several occasions mapping was conducted via canoe, otherwise mapping was conducted on foot. Primarily the remaining unmapped areas included uplands to the extreme north and south of the study area, and a region to the far southeast along and east of the Slate River.

On a typical excursion, team members would use 1: 24,000 scale topographic maps to delineate areas of high probability of bedrock or terrace exposure, and then follow group or individual traverses. Traversing was designed to maximize exposure in mappable areas. It was determined early in the project that due to low availability of outcrop in upland areas, these areas would receive less attention, and because of this there is a degree of bias in the subsequent interpretation. Over 540 total bedrock and surficial measurements were taken from 295 total sites averaging about 2 measurements per site (but ranging up to 10)

A site may be defined by the immediate area (less than 70 meters) in which an outcrop is located. Outcrops themselves are rarely larger than 10 meters, but many small outcrops on the order of 1 meter or less were located within a short distance of other small outcrops. Both groups of outcrops and single outcrops constitute a site. Data collected at a typical site included a lithologic description and possible sample. A total 149 samples were taken from all sites. Site measurements included foliation, bedding, cleavage, jointing and any lineation necessary to help determine general structure. Early in the project cleavage was distinguished from foliation, with cleavage being defined as a consistent, non-penetrative fabric in a rock, particularly evident along areas of breakage. Foliation is defined as a consistent penetrative fabric. Only a few sites recorded cleavage measurements, and they were later grouped in with foliation measurements that recorded similar readings in the area. When distinct bedding planes were observable, they were also measured, however it was often the case that bedding was parallel or subparallel to foliation, and the two were noted as such. In addition, a GPS point was taken using Trimble Geoexplorer GPS units. If GPS reception was unavailable, points were noted on topographic maps and less precise coordinates were taken from those maps. The Universal Transverse Mercator system was consistently used with a reference of the 1927 North American Datum. Notes about the location and setting of the outcrop were also taken, which included the general orientation of the outcrop, directions to the outcrop, any confounding or unusual factors about the outcrop that might be helpful for revisiting the site, and the weather.

On multiple occurrences, as is the case for many diabase dikes, the most consistent data was recorded in exposed “float” or large loose bedrock material. Any float used as a site was determined to be large and fresh enough to show little evidence of long distance travel; no structural measurements were taken on float. Saprolite was identified all across the study area; a few rare measurements were made on saprolite or weathered bedrock. This only occurred however, if the saprolite was determined to be the best exposure available and known to be in place. Lithologic descriptions were rarely made for saprolite other than to note large porphyroblasts or discernable alteration minerals. Each site was named using a nomenclature that included the date, relative order of site identification and individual responsible for the notes.

Surficial mapping of alluvial surficial deposits, including a number of terraces and floodplain sediments. These deposits were identified using a number of techniques. Typically team members would traverse to look for loose cobbles or gravels or cobble outcrops, indicative of an alluvial deposit. Many of these coincided with a sharp break in slope, identifiable on topographic maps, or in tree thrown craters. If cobbles were sighted, a strath elevation was approximated by locating the highest point of exposed bedrock (sometimes in the form of float) and taking eye height measurements to the apparent tread (large flat exposed surface). A strath elevation could then be calculated by subtracting the measured tread thickness from the tread’s elevation taken from a topographic map. If bedrock outcrop at a particular location was unavailable, but the location was very obviously an alluvial deposit, the strath surface was usually approximated by a drastic change in slope consistent around a majority of the exposed perimeter of the tread. Eyeheights were similarly taken from this slope change to approximate tread thickness. Multiple thickness approximations were made at a given terrace site, and this helped to improve the accuracy of strath elevations later used to reconstruct longitudinal profiles from correlated strath elevations.

Soil samples were taken by hand auger at suspicious sites to help determine their true origin. Augers were able to average depths of roughly two meters, taking samples approximately every 10 to 15 cm. These samples were documented in the field for Munsell soil color, approximate clay content, and ped structure, then later analyzed for clay concentration, particle size, and electrical conductivity by Lauren Parker. A consistent standard of alluvial surface was identified from known terrace locations to allow for comparison of suspicious sites.

Cobble lithologies were also taken from identified terrace exposures. This was intended to provide information about the history of catchment evolution of the James, and also assist in identifying to what channel a particular terrace was linked, as it was sometimes the case that large tributaries created their own terraces, which could be differentiated from James River terraces by the relative distribution of cobble lithologies. A description would include the lithology of the clast, including any observed sedimentary or metamorphic features as well as the degree of weathering and obvious signs of transport (e.g. chatter marks, gouges, bash marks).

Data compilation and synthesis was conducted upon return from the field. Field compilation occurred during early stages of summer mapping and was used largely to prepare for upcoming traverses and establish verified terraces or contacts. Upon return, samples were promptly cataloged by site and stored. Sites were entered into spreadsheet form that included data on their coordinates and elevation, and structural or surficial measurements, rock type, and any samples that were taken. This master spreadsheet was then subdivided into a spreadsheet containing surficial data points and bedrock data points for map construction.

Surficial and bedrock maps were originally constructed using ESRI ArcInfo, and were later touched up in Adobe Illustrator. A GIS based mapping software was chosen because it was able to preserve more detailed information for an individual site (all of the data in the original spreadsheet) and also because of the relative experience of both student collaborators in using ArcInfo. Due to the detailed nature of the ArcInfo software however, the nearly completed map was exported to Adobe Illustrator as a portable document for finishing.

To construct the map, a topographic map was first uploaded as a raster to serve as the base. This was washed out to grayscale and faded. Second, all sites were incorporated as a dBase file and reprojected as X/Y data points using UTM coordinates. The X/Y points were then converted to a point shapefile and automatically subdivided by pertaining information. These points could be reclassified even within divisions; for example, points were first divided into bedrock and surficial points and then subsequently to foliation, bedding and fracture measurements. Each data point could then be assigned a specific mapping icon and automatically rotated to account for its respective strike angle and dip direction. A site with multiple measurements of the same variety was averaged within a natural break corresponding to a difference of 10 degrees for strike and dip. This is a reasonable average, as there is roughly the same degree of human error that might occur in a field measurement. A site with multiple measurements of different varieties required manual relocation once all points had been plotted. Mapped linear and polygon features including terrace strath and treads, bedrock contacts and fold axes were uploaded from GPS units or drawn in by hand. They were similarly classified and represented on the map.

To determine lithologic units on the bedrock map a point map of sites was created by assigning all sites with lithologic data a respective color. All of this lithologic data was compiled from site evaluation during field mapping. Knowledge of the observed rock types and their relationships developed as mapping progressed, so a number of revisions were necessary to achieve a satisfactory outcome. From this point map it was possible to delineate plausible contacts that were consistent with observed contacts. Additionally, a similar point map was created for all structural measurements (before averaging). From this map naturally delineated areas of similar structure were isolated and plotted together on stereonets to approximate their most plausible structure. The idea behind this type of analysis is that general foliation trends (and bedding parallel measurements) may reveal distinct and different stereonet patterns for certain fold and fault patterns. This technique was based from Marshak and Mitra (1988), and includes first creating a scatterplot of poles to foliation, then identifying point maximum groups of foliations and plotting a great circle through the point maximums. These great circles represent an average fold limb (or opposing fault foliation). Differing point maximums should therefore fall along a great circle that represents the approximate plunge of the fold axis, and the angle separation between the point maximums can be used to characterize the fold (or, consequently if no data between maximums occurs identify the structure as a possible fault). This method is importantly an approximation, and may be hindered if data is not spatially dispersed.

Based on the observed structural data from the stereonet analysis, a cross section to 3000 ft. depth was created following the linearized channel valley within the study area. This profile is used to better illustrate the underlying geology over which the James flows, and demonstrate the correlation between the knickzone reach and observed lithologic or structural variance. This profile has no vertical exaggeration and a maximum of 20 ft of relief (relatively zero) due to channel alluvium. Because of this, the channel slope is barely recognizable.

To characterize lithologies and name units, a total of 18 thin sections were created from hand samples collected in the field. Certain samples were chosen for their consistency, relative importance and their general representation of an identified lithology. Thin section chips were prepared by the author using rock saws provided at William and Mary. Chips were mailed to Quality Thin Sections of Tucson, Arizona during two separate instances. All sections returned intact and were subsequently examined. The second set of sections, including 7 in total, unfortunately returned unpolished. This was a slight hindrance in their identification.

To identify thin sections, a petrographic microscope was used to account for all identifiable minerals and the general fabric or texture evident in the section. While a formal point count was not conducted, the construction of a list of all major identifiable minerals, including secondary and accessory minerals, with approximated proportions of the total lithology in addition to a description of general fabric including the relative degree of foliation was sufficient to accurately identify type lithologies for all units within the mapping area. This thin section data in conjunction with an amassed hand sample collection was enough data to ascribe rock names to each unit.

Surveying

Surveying of the low water surface was intended to increase the precision of channel longitudinal profiles, as it was observed that the profiles produced from 1:24,000 scale topographic maps do not accurately reflected the observed incision pattern within the knickzone and instead average the slope within its reach. Through surveying precision could be increased to centimeter scale and thus account for small scale slope variances within the channel. Identification of slope changes, even on a very small scale is indicative of differential hardness; as explained previously using the erosion rate equation. If this occurs, then there is direct evidence of differential incision and a lithologic control on the river.

Surveying occurred during two excursions that comprised two transects to the north and south of the east end of Big Island (figure 3). These transects represent a total of ~4 km, reaching a maximum of ~2.25 km upstream from the toe of the knickzone along the northern transect. Evident from aerial photos, this area experiences the largest drop within the knickzone, evidenced by the high concentration of channel outcrop (figure 6). Surveying was conducted using a Topcon GTS Total station and three prisms and accomplished using a two person survey technique. This required one person to man the total station and take measurements from a known basepoint with a known elevation and one person to wade in the channel with reflecting prisms. The base station operator would check to see if the total station apparatus was varying by periodically surveying a consistent point and comparing the measurements. Any discrepancies were noted. Because the total station stayed constant, survey point elevations were relative to the total station base point. The absolute position and elevation of this point was measured using a GPS unit and differentially corrected. Once this base point elevation was obtained, the entire profile was recorrected to a known elevation defined on a topographic map.

For the first transect (the southern side of Big Island), two channel traverses were conducted to account for lateral variation in outcrop. Only one traverse was conducted for the second transect (north side). During each excursion the river level was significantly lower than normal, on the order of one third its normal level for that date. This provided for ample outcrop exposure from which to survey. The low water surface was the chosen surveyed surface for two reasons. First, as the knickzone drops down over the surveyed reach, the water surface is a good proxy for the actual knickzone slope, which is observed to be variable. Second, surveying the river bottom (the only other feasible option) would in theory reflect a more accurate longitudinal profile, however this method would be extremely difficult and largely inaccurate since the river bottom varies considerably between a scoured bedrock surface and a thick alluvial cover. It would be nearly impossible to survey the bedrock river bottom, uninfluenced by the current bedload. Survey depth was also limited by the height of the human surveyor in the channel or how high that individual could hold the survey rod.

With the surveyed data points, two longitudinal profiles were constructed of the water surface. These points were compiled in Microsoft Excel and corrected from the base station, following which the real elevations were used to construct the profile in Adobe Illustrator. Profiles were constructed on a scale with a 42x vertical exaggeration.

This was necessary to emphasize the discrete steps observed in the knickzone. Notes on observed lithology, erosion mechanism and general outcrop morphology, taken concurrently with the surveyed points, were added to the profiles and from these a lithologic interpretation was created to underlie the profile. These surveyed profiles include a lithologic interpretation to best illustrate field observations regarding how the knickzone is incising, although, they are not complete balanced cross sections.

The northern transect was further analyzed to compare observed channel lithology with channel slope in an attempt to discern dominant ridge forming lithologies. These, by inference would be lithologies more resistant to erosion, and perhaps exhibiting a control on the longitudinal profile of the river. From the raw survey data, individual slopes were calculated between points. This first assumes a straight line distance between points, and does not account for lateral movement (thus actual slopes may in fact be larger than those represented). Lithologic data for this transect was recorded for nearly every site based on outcrop appearance on either a fresh face or scoured surface. Unitless slopes were then categorized by lithology and plotted as a scatterplot to see if any particular lithologies exhibited unusually high slopes.

Laboratory analysis

During the early stages of the project a variety of channel and valley profiles were constructed using 1:24,000 topographic quadrangle maps with a 10 ft. contour interval of the roughly 35 km up and downstream of the knickzone. These included longitudinal profiles of the main channel and its valley as well as longitudinal profiles of major tributaries. These profiles could be plotted together to discern the extent of knickzone development in the main channel, and comparatively, the tributaries. Cross valley profiles at 1 km intervals for the 35 km stretch were also constructed. These profiles extended 2 km away from the valley center along a line perpendicular to the linearized channel valley. These profiles were constructed to help identify terraces by looking for large flat surfaces along channel banks. It was later determined that the 10 ft contour interval was not a high enough resolution to accurately image the knickzone or associated terraces with any precision. Attempts to recreate higher resolution profiles using 30 m resolution DEMs were also unsuccessful. This factor was the driving motivation behind surveying the low water surface of the channel; a technique that will permit the creation of a profile with centimeter resolution. The accumulated data, however, was particularly helpful when paired with the original topographic quadrangles in identifying suspect terrace regions, despite that fact that the data was of too low a resolution to hypsometrically evaluate. This expedited later surface mapping and revealed new terrace deposits further downstream.

To determine the extent of structural control posed in the third research question an analysis of channel flow direction was conducted for two major tributaries feeding into the James River. Flow directions within the tributaries were linearized and represented in linear rose diagrams in the style of Tooth and McCarthy (2004), but of course modified to suit single meandering channels. The two streams were the Slate River and the Hardware River. These two tributaries were chosen for their length and sizeable discharge, spatial relation to the knickzone (the Slate feeds in downstream of the knickzone, and the Hardware feeds in to the uppermost reaches of the knickzone), and the fact that they flow over different lithologic units.

First, linearizing the channel was accomplished by tracing lines through the midsection of the channel based on 1:24,000 scale topographic maps, and where the channel bends, adjusting the line, and then measuring and recording the length and direction of flow. The resulting data was weighted by length. This was accomplished by normalizing the entire set to the lowest length. Thus the shortest channel section was categorized by its trend and received a value of 1 and the longest channel section was categorized by its trend and received a value equal to its multiple of the shortest section. Data was then represented graphically in a rose diagram using Stereonet software with petals divisions equal to 10 degree bins and lengths ranging from 25 to 35% of data. This technique was employed to illustrate any dominant trends of channel flow that might correspond to an observed structural feature such as a given joint set or foliation strike. Because each data set is normalized to its respective smallest unit, the resulting diagrams may not be directly compared to each other. They may, however, be compared to rose diagrams constructed using area specific foliation or joint measurements, and rose diagrams representing these measurements were constructed for this reason.

In an additional attempt to determine the extent of structural control with emphasis on the knickzone itself, a linearization analysis was conducted using aerial photos of the channel within the ~5 km knickzone. Here, ribs identified while surveying may be accounted for laterally (in addtion to their characteristic slope change) to determine if there is a structural influence to their strike.

High resolution aerial photos oriented perpendicular to the ground surface, with the surface oriented to north were taken using Google Earth software. The resolution of these photos was incredibly clear up to 1:4000 scale or larger, and cross channel ribbing was easily observable for analysis. Figure 6 includes an example photo at a smaller scale than was used for analysis. Cross channel outcrops were first linearized in discrete segments. As these ribs were continuous across the channel, in anabranching reaches the segments had to be correlated as to not double count strike measurements. A total of 64 outcrops were linearized. These planar features were then measured for their strike angle and these angles were plotted in a rose diagram using the same Stereonet software. Petals for these diagrams constituted 10 degree bins with lengths corresponding to 25% of data.

Several other rose diagrams were created using local and total foliation and fracture data compiled during mapping. Here, measurements could be easily compared with the aerial photo and channel linearization diagrams to determine correlation. To create these, first fracture and foliation data were subdivided into individual spreadsheets; foliation parallel bedding was included in the foliation data set. These measurements were then plotted on rose diagrams with petals corresponding to 10 degree bins with maximum lengths equal to 25% of the data. The same analysis was conducted for fracture and foliation data in specific areas around the Hardware and Slate Rivers so that they might be compared to the linearized flow analysis.

Results

Mapping

The finished bedrock and surficial map of the study is presented as figure 7. Three primary units are contained within this area, with associated subunits and cross cutting features. The western half of the study area is composed of metasedimentary rocks, largely identified as metagreywacke after which the unit is named. The unit, however, locally contains quartzose metagreywacke that commonly exhibits a “pinstriped” lineation that follows local deformation (figure 8), metaarkose and quartzite. These rocks have been metamorphosed to the greenschist facies and highly deformed, although deformation is locally variable. Deformation in this unit is typically a continuous penetrative s-type foliation, however (as previously mentioned) more quartz rich areas tend to contain an l-type lineation of accessory minerals. Note, however, that this foliation may be an overprinted foliation from a later deformational episode; however no examples of intersecting foliation from multiple deformational episodes were found. A few outcrops containing bedding were found, particularly along the southern reach of the Hardware River. Both the Smith *et al*. (1964) and Brown (1969) maps cite evidence of overturned graded bedding in this area. Although bedding was observed there was no clear evidence of graded bedding, and thus no sedimentary evidence that the unit has been overturned. Bedding planes will stand out in outcrop because beds will exhibit coarser grained angular clasts, these coarser beds have been interlayered, but do not exhibit graded bedding. These rocks do exhibit mesoscale open to isoclinal asymmetric folding, which have been previously interpreted by Brown (1969) to be drag folds.

This unit has been cross cut by north-northeast trending greenstone dikes (figure 7). These dikes are interpreted to have had a basaltic origin, metamorphosed to the greenschist facies based on their thin section mineralogy containing epidote, amphibole and an abundance of chlorite (Appendix I, D). The unit has also been crosscut post-metamorphism by northwest striking diabase dikes. Notably, these northwest cutting dikes are anomalous to the region; more typically howerer, these dikes trend north to northeast. This diabase contains elongate medium grained plagioclase (dominantly albite) and orthopyroxene with a classic ophitic texture (Appendix I, L). In thin section, the metagreywacke unit exhibits a mineral assemblage that includes quartz, chlorite, muscovite, feldspars, carbonates (likely calcite), opaques (dominantly subhedral to euhedral pyrite) and biotite, approximate composition varies locally. Appendix I, sections E,F,G,H,I and J represent the variety of compositions, grain sizes, clasticity, and fabrics seen in this unit.

In north to northeast striking gradational sedimentary contact with the metagreywacke lies a similarly composed mélange with metasedimentary matrix. This is a gradational boundary where the mélange is inferred to represent a slightly different sedimentary facies that experienced a higher grade of metamorphism and deformation. It is not a separate unit, however, but is lithologically distinctive enough to be mapped as a sub unit of the metagreywacke. Pavlides (1989) chose to map this unit separately due to its distinctively high magnetic anomaly. The boundary for this sub unit corresponds to the westernmost observed exposure of definitive greenstone blocks, as observed from the best exposure in and along the James River. This unit contains allochthonous blocks typically on a meter scale of metabasalt, ultramafics, and quartzite. The unit has been metamorphosed to at least the greenschist facies, as the metabasalt blocks are now greenstone and the ultramafic blocks are nearly at the amphibolite metamorphic facies. The unit increases in deformational complexity over a short distance moving west to east, with rocks along the easternmost contact of a gneissic fabric that incorporate blocks into the deformation. Typically the rocks are complexly deformed schists with well developed micas that exhibit mesoscale folding around blocks (figure 8).

This mélange unit contains a tonalite dike based on thin section mineralogy, which does not appear to be allochthonous due to its relatively undeformed state and lack of fabric. The unit has also been crosscut by the same diabase dikes of the previous unit, however these dikes trend north to northeast. Also worth noting, this unit has been more complexly fractured, and contains more quartz and carbonate veins than other units. In thin section this unit exhibits roughly the same mineral assemblage as the metagreywacke, as the mélange matrix is a very similar metasedimentary rock. The rocks typically contain a larger amount of chlorite, epidote and carbonates; the first from the increased presence of greenstone and the latter from metamorphic fluids. Opaque minerals in this unit also tend to be euhedral pyrite and are significantly larger, to several cubic millimeters in outcrop (Appendix I, A and K).

A diabase dike cuts the easternmost portion of this mélange on the northern bank of the James River; it is inferred to have intruded along the boundary between the mélange and a separate unit of metasedimentary and metavolcanic rocks. These rocks have a very similar fabric and composition; the key difference being that clastic components appear to have distinctly volcanic origins exhibited as finer grained, angular rhyolitic or andesitic clasts. Brown (1969) and Smith *et al*. (1964) both identified the protolith of the western metagreywacke units as volcanic. There was no indication of this based on field or thin section evidence, so the protolith of that unit will be assumed to be simple sedimentary. This eastern metavolcanic unit, with areas of similar metasedimentary compositions is observed to have a noticeably volcanic protolith and thus is different enough from the western units to be mapped as a different unit. This metavolcanic and metasedimentary unit is comprised of arkosic and quartzose metavolcanic and metasedimentary schists with a sub unit of intertonguing muscovite schist. Locally within the unit, areas of higher metamorphic grade contain large (~5mm) euhedral cubic minerals that are inferred to be pyrite, (Appendix I, B). These rocks have been previously identified by Evans and Milici (1994) and the 1993 State Geologic Map of Virginia as correlative with the eastern Chopawasmic Formation which includes metavolcanic schists of similar composition.

To the east of these metavolcanics is a near vertically foliated slate belt, which has been consistently interpreted to be the Arvonia Formation. The contact here has been interpreted by Evans and Milici (1994) to be unconformable with the underlying metavolcanics. The Arvonia Formation contains slate and porphyroblastic slate and schist with biotite porphyroblasts. The slate has very good planar cleavage which has made it highly accessible for mining within this area. No garnet was observed in this unit, or within any other rocks within the mapping area. This is consistent with the location of the previously interpreted garnet isograd mapped to the southeast by Smith *et al*. (1964). No thin sections of the Arvonia Formation were made, because it has been extensively studied already. However it was sampled along with its sub unit the Bremo quartzite.

This research does not include a geochronology of mapped rock units, as they are not necessary in evaluating the structural and lithologic controls on the knickzone. For continuity however, they are included on the map as they have been reported by the most recent sources. The metagreywacke unit is interpreted to be Cambrian to late Proterozoic in age based on the 1993 Geologic State Map of Virginia. The mélange is identified to be Ordovician in age, based on the aforementioned observance by Pavlides (1989). If the metavolcanic unit is related to the Chopawamsic Formation, it is Ordovician in age based on U-Pb ages be Coler *et al*. (2000). The Arvonia Formation has long been determined to be Ordovician in age based on its observed fossil assemblage. Cross cutting dikes have most recently been interpreted to be Jurassic in age (Kunk, 1992), and greenstone dikes in the western portion of the study are of an undetermined age.

The study area has a general structure consistent with what has been viewed as typical of the Piedmont. Vertical to near vertical north/south striking foliation is continuous across the study area. The continuity of this foliation across several lithologic boundaries is curious and may reflect a deformational overprinting by a more recent deformational event than the one that placed these units to begin with. It is with this in mind that the structure should be considered. Comparative stereonet analysis of specific regions of the study area reveal possible isoclinal folds in the form of two synclines and an anticline striking parallel to foliation and located in the eastern half of the area which is consistent with a generally observed higher degree of deformation in this area. The easternmost syncline has been mapped along the Long Island syncline, and represents a tight synform structure enclosing a portion of the overlying Arvonia slate. These folds are based on observed variances in foliation and foliation parallel bedding on either sides of a fold as observed in outcrop along the channel.

The study area has been fractured in a relatively consistent pattern. Both foliation and fracture are plotted in figure 9 and show a preferred orientation. Foliation has a preferential strike of 30 to 40° and fractures display a dominant set striking approximately 310°, and perhaps a conjugate set at roughly 070°. The local fracture and foliation patterns around the Hardware River and Slate River in the west and east of the study respectively do not exhibit any significant variance pattern (figure 9). The maximum variance is a 20 degree change in dominant fracture orientation across the study area. There is no significant change in foliation strike across the study area. This indicates that while fracture and foliation strike patterns may vary locally they do not vary much regionally.

Five confirmed terrace levels were identified by Parker (2007) to represent a total of three profile levels. The straths were correlated based on either field observations or sedimentary characteristics. Parker (2007) found these terrace straths to correlate at different elevations that form a downward sloping profile mirroring the current profile surface. Deposits are concentrated along the outside perimeter of the channel just past inflection points in the channel and straths step down towards the river in these areas. Parker correlated the 5th highest terrace level to a ^{10}Be cosmogenic radionuclide age of ~1.1 Ma as measured by Felis (2003) several kilometers upstream.

Correlation of these absolute dates with sequenced terraces mapped along the knickzone allowed Parker to reconstruct longitudinal profiles representing a paleo river surface. Figure 10 illustrates these reconstructions. Strath sequencing of terraces within the study area were determined by using relative age estimations of terrace treads using an in-depth soil analysis that included measurements of clay concentration, grain size and electrical conductivity. Parker's reconstructions show a constant longitudinal profile through time which mimics the current profile. This is indicative of a stationary knickzone.

Surveying

Two longitudinal profiles assembled from survey data, and illustrated with lithologic and structural observations of the knickzone are shown in figure 11. These profiles depict a stepped pattern of relief where elevation drops drastically in multiple discrete locations, not at all consistent with an average slope of 1.8 m/km. Field observations made while surveying this transect indicate that these steps correlate highly with the location of greenstone blocks, quartz veins and the tonalite dike crossing the channel at this point. Foliation is observed to vary significantly in this region and appears to be due to the complexity of local deformation. Dominant bedrock erosion mechanisms were noted when obvious on channel outcrops.

Along the ~1.5 km southern transect there are a total of 6 discrete steps that total ~50% of the total elevation change. The profile begins on a diabase dike that has been complexly fractured and follows the river downstream. Fractures here are closely spaced (relative to the surrounding bedrock) which leads to a prevalence of plucking and potholing along intersecting fracture planes. Just downstream of this dike there is a long overdeepening, the surface of which is covered in alluvium. Further down stream there is a sequence of discrete knicks corresponding to localized lithologic differences with harder lithologies (namely quartz and greenstone) forming outcrops above the water surface. Quartz and greenstone commonly occur together, in a complexly deformed fabric. These ribs often exhibit potholing on their lee side and an upstream dipping abraded face on their stoss side. Potholing is evident to a higher degree in ribs in closer succession and experiencing more turbulent waters. Midway along the profile there is a large outcrop determined to be primarily composing a tonalite dike. This dike is massive and characterized by potholing, abrasion and large impact marks. Further downstream there are fewer greenstone ribs but some do occur and exhibit a higher fracture density than upstream ribs. These outcrops also exhibit a higher degree of plucking.

The northern transect constitutes ~2 km up from the toe of the knickzone. It exhibits a total of 11 discrete steps along this profile that account for approximately 60% of the total elevation change. Downstream, the profile exhibits a series of sharp steps that form cross channel ribs. They are observed to be due to locally high concentrations of greenstone and quartz that form elongate bodies across the channel. These outcrops are dominantly potholed and abraded, and they exhibit very minor fluting. Downstream of these steps there is a long, relatively shallow flat covered in alluvium. This alluvium appears to protect the area just downstream of a large rib. It may itself be located in the eddy of that rib. Downstream grading of alluvium was not obvious in this reach. Further downstream there is another succession of steps interrupted by a diabase dike. This dike exhibits the same high density fracturing and plucking and is assumed to be a northern portion of the dike seen in the southern transect. Steps up and downstream of this dike exhibit distinctly large blocks of greenstone with bright green epidote visible along scoured faces. Along these ribs, flow is temporarily deflected parallel to foliation, also approximately parallel to the rib. Some of these ribs have been plucked to the point where whole sections of the rib have been removed. Downstream there is another alluvium dominated flat that appears to be at once protecting the bedrock from direct erosion and protected itself by an upstream outcrop. There are a few greenstone dominated ribs towards the end of the profile; these exhibit a very high degree of potholing and correlate with the highly potholed outcrops midway through the southern transect. The profile ends when it reaches the same tonalite dike observed in the southern transect. Here the dike is massive, and exhibits a very high degree of potholing.

Further graphical analysis of the northern survey transect is depicted in figure 12. There are three lithologies that exhibit characteristically high slopes; these are greenstone, tonalite and metasedimentary mélange matrix. Quartz, as explicitly measured in this analysis did not show differentially high slopes. This is contradictory to field observations made while surveying and this discrepancy is indicative of methodological flaws either in this slope analysis or in field observations; less likely in the latter. This slope analysis is primarily flawed in two ways: first the slopes calculated are not necessarily parallel to flow following the actual longitudinal profile of the river, since there was a certain degree of lateral movement between surveyed points and the slopes represent a straight line distance between individual points. Second, the results are dependent on the number and placement of individual survey points; with a higher density point count, resolution increases and there is likely not a high enough resolution to discern complete trends for all lithologies.

Laboratory analysis

A longitudinal profile of the main channel 250 km upstream of the 60 ft contour in Richmond is presented in figure 1 along with a profile of the knickzone and five associated tributaries between 105 and 130 km upstream. These profiles were originally created by Lauren Parker previous to summer field work. These profiles show the knickzone to be a profile convexity with a slope of 1.6 m/km. Profile slope immediately upstream averages 0.255 m/km and immediately downstream averages .53m/km. Tributary profiles feeding into the main channel up and downstream of the knickzone demonstrate steepened profiles with indications of knickzones ranging from 20 to 50 ft up the channel profile.

Rose diagrams in figure 9A and 9B, illustrate foliation and fracture patterns for the entire study area. Foliation follows a dominantly 30 degree strike with a 20 degree range that encompasses nearly 50% of the data. Fractures follow a dominant 120-130 degree strike comprising 16% of the data, with significant fractures in a 30 degree range from 90 to 120 degrees. There is a minor strike representation at 70-80 degrees that may represent a less prominent joint set with the dominant fractures. These fractures indicate maximum stresses orientated to the southeast and northwest of the study area.

Preferential flow directions of the Slate and Hardware Rivers are depicted in linear rose diagrams in figures 13A and 13D. Recall that these rivers lie just downstream and upstream of the knickzone, respectively. Rose diagrams of local fracture and foliation data for each respective region are presented for comparison. The Slate River exhibits a definitive preferential trend of 90 to 100 degrees. There is a slight correlation to local fracture strike, which improves if compared to fracture data from the entire study area. There is no observable correlation to foliation strike and this does not change with the encompassing data region. Note that the data represented locally for the Slate River had to be extrapolated from measurements taken just north around the Slate-James confluence because the Slate river area remained largely unmapped. These measurements are highly concentrated in that region to several specific sites and the assumption that localized structure is the same in both areas is not well represented in the results.

A linear rose diagram representing flow direction of the Hardware River shows a dominant flow direction of 120-130 degrees that represent 21% of the data. Compared to localized fracture data taken from the region around the Hardware there is a strong correlation with the dominant 120-130 fracture strike. There is little to no correlation with local foliation strike data. This is higher quality data as the Hardware River area was twice mapped by foot and canoe.

Figure 6 displays results from the linearized aerial photo analysis. A photograph showing linearized channel ribs is also shown. Cross channel rib strike shows a dominant strike of 30-40° that is equal to 39% of the data, there is also a strong concentration of strikes at 20-30°. This data shows a strong correlation to foliation across the entire study area, aligning along a preferential 30° strike. There is no correlation to fracture data across the entire study area.

Discussion

Knickzone evolution

We can characterize the long-term evolution of this modern knickzone as stationary, in concurrence with Felis (2003) for several reasons. First, reconstructed longitudinal profiles based on terrace straths by Parker (2007) incorporating ^{10}Be dates from Felis (2003) indicate that the knickzone has remained in its current location within the last ~1 Ma. As indicated in figure 10, reconstructed longitudinal profiles mimic the modern day profile, indicating that the knickzone has not migrated upstream over the last ~1 Ma.

Additionally, there is an observed correlation between the location of the knickzone and the variable hardness of the lithologic units within the majority of the knickzone. Here, evidence comes from field observations of outcrops within and along the main channel, primarily located over the final few kilometers of the knickzone. Here, surveyed profiles of the knickzone demonstrate a clear correlation of discrete steps to differentially harder lithologic blocks within the mélange unit. 50 to 60% of the elevation change occurs at these steps which demonstrates a clear lithologic dependence within this region of the knickzone. Taken as a whole, this mélange unit is differentially harder to erode and the channel must increase its slope across this unit to maintain a consistent erosion rate.

This lithologic influence alone is not indicative of a stationary knickzone. It is the lack of discrete knicks, even the lack of exposed outcrop within the channel upstream and downstream of this area that indicates that the knickzone is constrained in this particular area. A stationary knickzone is thus implied through the correlation of this area with the mélange-metavolcanics contact that lies directly at the base of the knickzone as well as the differential erosion observed along survey transects that correlates very closely to lithologic variance within the mélange unit.

Complicating this stationary interpretation however, is the presence of migratory knickpoints in tributary channels upstream and downstream of the main channel knickzone. We assume that these knickpoints are migratory due to the fact that they lack the same characteristics defining the main channel knickzone as stationary. Namely, they do not all correlate to lithologic boundaries between units (at least not explicitly mapped) and they have not all been observed to erode differentially along lithologic heterogeneities within a particular unit (Figure 14).

Assuming that they are migratory, they might be explained by either of two possible scenarios that would also explain the observed high incision rates recorded by Felis (2003). First, a pulse of incision lowered the entire main channel profile at a suddenly increased, but temporary, rate. This relative base level change spawned migratory knickzones along the tributaries. A pulse like this might have been accomplished by a sudden influx of sediment or increased discharge perhaps in response to climatic variability. Dunford-Jackson (1975) and Harbor *et al*. (2005) observed rapid incision rates locally within the Piedmont as well as Reusser *et al*. (2004) further north. They also identify relatively short time scales for these rapid incision rates (e.g. Reusser *et al*. identified a ~20 ka period where incision rates were an order of magnitude larger than the long term average), dramatic changes in incision rate compared to the long term (~1 Ma or greater) average witnessed over short times scales indicates that a pulse of incision is likely the cause of longitudinal profile lowering, relief generation and landscape disequilibrium.

Second, at least one migratory knickzone may have moved up the longitudinal profile of the James at some point in the past. This main migration originally caused by eustatic sea level fall, spawned migratory knickzones along the tributaries. Pazzaglia and Gardner (1993) depict at least four instances of sea level transgression within the last 1 Ma. Knowing that the speed of upstream movement of a knickzone is dependent on the upstream component of the erosion rate, we infer that the speed is also proportional to the catchment area through its relation to stream power in the stream power equation (Howard and Kerby, 1983). The speed of a knickzone upstream migration diminishes as the area of the catchment from the point of the migrating knickzone diminishes (Sklar and Dietrich, 1998). This means that a migrating knickzone slows down as it approaches its headwaters. Of course, as the knickzone migrates it may incise through differentially harder lithologies, temporarily slowing its migration. Practically, this is very difficult to observe because the slope is continually increasing as the knickzone migrates. Given this assumption, it is entirely possible that a knickzone (or knickzones) migrating upstream in the main channel have moved far out of the study area and relaxed into the longitudinal profile. This migration spawned smaller tributary knickzones, however, which are still approaching their headwaters. If this were the case, knickzones located downstream of the knickzone should have knickpoints further up their profile than upstream tributaries (as they have been moving upstream longer), which does not appear to be the case, based on tributary longitudinal profile and field observations illustrated in figure 14.

The evidence presented through field mapping, surveying and longitudinal profile analysis demonstrates that the James River knickzone in question is in fact stationary. There is evidence of migration preserved in tributary knickpoints, however. These migratory knickpoints indicate that either a temporary pulse of erosion incised the entire channel along the longitudinal profile, spawning migratory knickpoints by the process of base level drop; or that a migratory knickzone itself due to base level drop spawned these knickpoints as it passed through the knickzone reach sometime within the past ~1 Ma. Of these two possibilities the first is preferred due to variable distribution of tributary knickpoint distances upstream of the main channel, and because of its record in other areas of the Piedmont.

Incision

Scale is key to understanding the precise mechanisms of incision across the knickzone. At a large scale, the knickzone itself is stationary incising gradually downward; but at a smaller scale incision is very different. Here we can break up the entirety of the knickzone into a sequence of smaller knickpoints located at the observed discrete steps in the surveyed profile. Each of these individual knickpoints incises, and it is the sum of these individual incisions that controls the rate at which the entire knickzone incises. Whipple *et al*. (2000) identified a similar scenario in a bedrock knickzone of mixed lithology with differential hardnesses. Incision raises areas of differential hardness that may appear to migrate upstream or downstream dependent on local lithologic or structural characteristics. In this way the total incision of the reach is concentrated at various points along its length (Hancock, 1998).

Erosion mechanisms acting on an individual knickpoints are controlled by the site-specific structure and lithology, which is highly variable within this mélange. At the relative scale of an individual knickpoint, channel stream power can be extreme. Thus erosion of these resistant ribs may be rapid to episodic. An example here is a plucked or potholed rib. Taken at the scale of this individual knickpoint, incision is extremely rapid or episodic. However regarding the knickzone in its entirety incision is very gradual.

The James is a mixed bedrock and alluvial river, and so this model should reflect the additional influence of a partial alluvial cover. A modified version of the model of individual knickpoint incision from Whipple *et al.* is illustrated in figure 15. Based on observations within the channel, alluvial deposits develop in eddies behind resistant ribs. This alluvium acts to temporarily armor downstream bedrock from direct erosion. It loses influence however, as the outcrop protecting it erodes away. The size of the eddy behind a rib, and thus the extent of deposited alluvium in that eddy is proportional to the size of the protruding rib. As this rib is eroded, the down stream alluvium is increasingly carried away and more downstream bedrock is exposed to direct erosion.

In well-foliated outcrops, observed both in the main channel knickzone and in knickzones along tributaries, channel flow incises parallel to foliation. Figure 16 illustrates this concept along two tributary knickzones that have been dissected along foliation planes. At such a site, flow moving down an individual knickpoint surface (perhaps a fracture plane or exposed channel rib) moves parallel to foliation planes and dissects the outcrop in this parallel pattern. In a more massive, finer grained lithology composed of differentially harder minerals, such as a greenstone block or quartz vein, this pattern does not occur. Thus, a knickpoint is eroded parallel to foliation to expose a differentially harder lithology. It is likely the case that the observed correlation of main channel ribbing with foliation strike across the study area is due to this general pattern of incision.

Structural and lithologic controls

Whether or not the channel is hydrodynamically or structurally controlled within this area appears to be dependent on the discharge of the channel, or perhaps more specifically, the width of the channel. In the main channel, morphology is not apparently structurally controlled. The wide anabranching reach flowing sub-perpendicular to lithologically controlled ribs does not indicate any level of structural or lithologic control on the flow direction in the channel. At a large scale, flow in the main channel does not correlate with foliation, fracture sets or any general structural feature. However, at a smaller scale there is a pronounced structural and lithologic control. Results from surveying and aerial photo analysis illustrate this relationship which appears to be both lithologic and structurally influenced. For example, harder lithologies within the mélange have been elongated along strike of foliation, likely deformed into the complex fabric of the unit. This structural-lithologic relationship becomes obvious when erosion reveals cross channel ribs parallel to strike of foliation. The main channel within this reach is dominantly hydrodynamically controlled however, there is a structural influence on the small scale incision mechanisms within its reach (Richardson and Carling, 2005).

At a larger scale than the cross channel ribs, yet smaller than the entire knickzone reach, tributaries such as the Hardware and Slate Rivers exhibit a strong correlation to structural patterns. The channel linearization analysis indicates that angularities in both channels correlate highly with local fracture data. This evidence reveals that these channels are structurally controlled relative to the main channel. Recognizing that the main channel and these tributaries overly the same general structure, it is curious why the tributaries conform to structural features but the main channel does not.

These tributaries must be eroding at rates very similar to the main channel, otherwise we would see pronounced knickpoints at their confluences, thus it is not likely a differential stream power between the tributaries and main channel determines the extent of structural influence. It may be the significant difference in width between the two channels that determines the degree of structural influence on channel flow direction. The width of the tributary may be less than the typical distance between major fractures forcing the channel to follow only one at a time. In contrast, the width of the main channel is large enough to exploit multiple fractures at once and thus not exhibit any particular correlation to fracture pattern. This would explain the high correlation between fracture patterns and flow direction observed in the tributaries, but not in the main channel.

The main channel does not appear to be controlled at all by the individual lithologic variances that form ribs across it. The combination of ribs, or more accurately the heterogeneity of hardness of the unit does have an effect on the channel. In fact, this is very likely the dominant control on the placement of the knickzone. So the degree of litholgic, and structural control on the knickzone is scale dependent. At the scale of an individual rib, the well developed bedforms and extreme incision are indicative of a hydromorphically controlled channel where the bedrock erosion is entirely controlled by the flow through the channel (Richardson and Carling, 2005). At an intermediary scale, the scale of tributary channels, there is a significant correlation to fracture patterns. It is likely that for narrow enough rivers, flow is preferentially directed along major fractures as it travels down to the main channel. Similar results at this scale have been observed by Wohl and Ikeda (1998). The largest scale, the scale of main channel exhibits a lithologic control on its slope, locally manifested as a stationary knickzone.

Landscape disequilibrium

Knickzones are characteristic of disequilibrium landscapes. It is possible in a landscape undergoing dynamic equilibrium to maintain a stationary knickzone due to differential lithology. However, there are still indications of landscape disequilibrium preserved in our study area. First, the observed presence of migratory knickzones within tributaries of the main channel as well as the record of incision recorded in main channel terraces indicate that the James River must have differentially incised at some point within the last ~1 Ma in order to generate these knickzones. To do this the James River must have dropped relative to the tributaries, and migration was spawned by base level change relative to the main channel. It is possible that either the main channel experienced knickzone migration or a pulse of incision along its longitudinal profile. The latter is the likely scenario here is more likely.

Of the three most commonly cited mechanisms of disequilibrium; including a profile wide incision event, a migration of incision upstream from base level of the channel profile, or flexural uplift of bedrock underlying the channel, the first is preferred. Base level fall may be responsible for contributing to incision, but is not likely the dominant influence because the rate of eustatic transgression may have been too slow to have generated a significant convexity in the profile of a large channel (Schumm 1977). Pazzaglia and Gardner (1993) described at least four transgressions in the Salisbury embayment within the last ~1 Ma, and Haq (1987) calculates that there could be ~150 m of sea level drop during the last 15 Ma.

The modeling of flexural uplift conducted by Pazzaglia and Gardner (1994) indicate only a possible 35-130 m of uplift over the past 15 Ma, enough to contribute to incision but not enough to account for observed incision rates on the order of 600-800 m/Ma observed by Reusser *et al*. (2004) along the Susquehanna and inferred to have pulsed over a 20 ka time scale. This makes profile wide incision the most likely cause for disequilibrium in this area. Fluctuating climate, observed by Peizhen *et al*. (2001) to have increased globally 2-4 Ma may have created incisionary pulses by repeatedly increasing one of these factors over a short (~10 kyr) time scale by increasing total discharge or bedload discharge (Sklar and Dietrich, 1998). This, may have also occurred due to fluctuations at a higher level over a longer time scale as sediment supply has both an erosive and an armoring effect depending on its ability to maintain entrainment in a flow (Sklar and Dietrich, 1998). Either of these possibilities is possible for a variable climate scenario, and in fact may have been efficient at differentially incising on both time scales.

Conclusions

Reconstructed longitudinal profiles of the knickzone in conjunction with a distinct lithologic dependency observed in two survey transects at the base of the knickzone indicate that this knickzone is stationary and lithologically controlled by a differentially harder mélange unit in contact at the toe of the knickzone. Incision in this area is variable and highly dependent on local fabric and lithology. Throughout this reach incision in the main channel does not appear to be structurally controlled, although lower discharge tributaries confluent upstream and downstream of the knickzone do appear to be so controlled. Despite a hydrodynamic control of incision the knickzone is interpreted to be stationary. However, this interpretation is complicated by the presence of migratory knickzones in tributaries intersecting the main channel above, within and below the knickzone. These migratory knickzones are most likely the result of pulsed incision along the profile of James River in response to climate induced temporary bedload discharge and are indicative of landscape disequilibrium in the area.

Further Research

It may be an interesting project investigating the presence of the anabranching alluvial islands within this reach. Tooth and McCarthy (2004) suggested a positively reinforcing feedback whereby alluvium would develop in an outcrop eddy and after achieving a maximum surface area vegetation. Vegetation solidifies the alluvium and allows it to grow in surface area, promoting more vegetation. Sparse vegetation was observed in some smaller alluvial deposits occurring in outcrop generated eddies. Perhaps it is this type of ephemeral alluvial deposits which eventually develop into islands.

Additionally, there is an outcrop at the very base of Big Island within the toe of the knickzone. This is an incredibly interesting site from a geomorphic and structural point of view. An interesting project might test the theory mentioned earlier in this thesis that there is a distinct spatial distribution of dominant bed forms and bedrock erosion mechanisms corresponding to different areas of a knickzone. For example potholing is dominant at the base of the knickzone, or in a more dramatic example in a plunge pool. Another possibility is to collect rock mass strength measurements to quantitatively determine the hardness of individual rock types to better constrain what the precise lithologic control are within this location. Due to the large bedrock exposure this would be an optimal place to start, and it may also be a worthwhile picnic location.

Finally, a more complete set of cosmogenic radionuclide dates on terraces within the knickzone would better constrain incision rates, and provide a better temporal record of incision for correlation to other records of climate variability or sea level fluctuation. Of course, the quality of cosmogenic radionuclide sites is important and the resulting ages are sensitive to a number of possible disturbances found to be common within this area.

Acknowledgements

I would first like to thank fellow collaborator and friend Lauren Parker for providing a wealth of insight for this project. I would also like to thank my advisor Dr. Greg Hancock for continued support, encouragement, ideas and excitement throughout the entirety of the project. Thanks to Dr. Chuck Bailey for help with the structural and map analysis, to Dr. Brent Owens for assistance in thin section descriptions, and to Crystal Lemon and Graham Lederer who assisted with fracture data collection in a portion of the study area. Additionally I would like to thank Dr. Sarah Stafford for serving on my thesis committee with the previously mentioned individuals. This project was largely funded by a USGS EDMAP grant and a William and Mary Charles Center Batten Scholarship for scientific research.

References

Brown, W.R., 1969, Geology of the Dillwyn Quadrangle, Virginia: Charlottesville, Virginia Division of Mineral Resources, 77 p.

Brown, W.R., 1986, Shores Complex and mélange in the central Virginia Piedmont, *in* Anonymous, ed., Southeastern section of the Geological Society of America, Volume 6: Centennial field guide: United States (USA), Geol. Soc. Am., Boulder, CO, United States (USA).

Coler, D., Wortman, G., Samson, S., Hibbard, J., Stern, R., 2000, U-Pb geochronologic, Nd isotopic, and geochemical evidence for the correlation of the Chopawamsic and Milton terrances, Piedmont zone, southern Appalachian orogen: Journal of Geology, v. 108, pp. 363-380.

Dunford-Jackson, C.S., 1978, The geomorphic evolution of the Rappahannock River basin [PhD thesis]: University of Virginia, Charlottesville, Virginia.

Dury, G.H., 1964, Principles of underfit streams: US Geological Survery Professional Paper 452-A, 67 p.

Evans, N.H., 1984, Lithofacies of the Virginia Blue Ridge and hardware terranes: evidence for pre-Middle Ordovician volcanic arc accretion, *in* Latest Precambrian to Ordovician metamorphism and orogenesis in the Blue Ridge and western Piedmont, Virginia Appalcahians [PhD dissertation]: Virginia Polytechnic Institute and State University, Blackburg, Virginia, 313 p.

Evans, N.H., and Milici, R.C., 1994, Stratigaphic relations and structural chaos on the southeastern limb of the Blue Ridge Anticlinorium and points east, central Virginia piedmont, *in* Fieldguides to southern Appalachian structure, stratigraphy, and engineering geology: Southeastern section Geological Society of America guidebook number 10.

Felis, J., 2003, Terrace studies and knickzone charachterization on the James River, Virginia Piedmont, [undergraduate thesis]: College of William and Mary, Williamsburg, Virginia, 33 p.

Frankel, K. L., Pazzaglia, F.J., Vaughn, J.D., 2007, Knickpoint evolution in a vertically bedded substrate, upstream-dipping terraces, and Atlantic slope bedrock channels, GSA Bulletin, v. 119, no. ¾, pp. 476-486.

Gilbert, G.K., 1877, Report of the geology of the Henry Mountains, geographical and geological survery of the Rocky Mountain Region: Government Printing Office, Washington DC.

Hack, J. T., 1957, Studies of longitudinal profile streams in Virginia and Maryland: U.S. Geolological Survey Professional Paper 294-B, pp. 45-97.

Hack, J.T., 1960, Interpretation of erosional topography in humid temperate regions: American Journal of Science, v. 258-A, pp. 80-97.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, pp. 1156-1165.

Hancock, G.S., 2007, Investigation of knickzone evolution through surficial and bedrock mapping on the James River, central Virginia Piedmont: EDMAP Proposal: Unpublished Information.

Hancock, G., and Kirwan, M., 2007, Summit erosion rates deduced from ^{10}Be: Implications for relief production in the central Appalachians: Geology, v. 35, no. 1, pp. 89-92.

Hancock, G.S. Harbor, D.J., Felis, J., Turcotte, J., 2004. ^{10}Be dating of river terraces reveals Piedmont landscape disequilibrium in the central James River basin, Virginia, *in* Proceedings, Southeast Region Geologic Society of America, Knoxville, Tennessee, March 23-24.

Harbor, D.J., Bacastow, A., Heath, A., and Rogers, J., 2005, Capturing variable knickzone retreat in the central Appalachians, USA: Geogr. Fis. Dinam. Quat., v. 28, pp. 23-36.

Howard, A.D., and Kerby, G., 1983, Channel changes in badlands: Geological Society of America Bulletin, v. 94, p. 739-752.

Kunk, M.J., Froelich, A.J., and Gottfried, D., 1992, Timing and emplacmeent of diabase dikes and sheets in the Culpepper basin and vicintity, Virginia and Maryland: ^{40}Ar/^{39}Ar age spectrum results from hornblende and K-feldspar in granophyres, abstract: Geological Society of America Abstracts with Programs, v. 24, no.2, p. 125.

Marshak, S. and Mitra, G., 1988, Basic Methods of Structural Geology: Prentice Hall, New York, 446 p.

Parker, L. B., Lang, K.A., Hancock, G.S., 2007, Evidence for knickzone propagation and landscape disequilibrium along the James River, central Virginia Piedmont, Eos Transcripts AGU, 88(52), Fall Meeting Supplement.

Pavich, M.J., 1989, Regolith residence time and the concept of surface age on the Piedmont “peneplain:” Geomorphology, v.2, pp. 181-196.

Pavlides, L., 1981, The central Virginia volcanic-plutonic belt: and island arc of Cambrian (?) age: U.S. Geologic Survey Professional Paper 1231-A, pp. A1-A34.

Pavlides, L., Arth, J.G., Daniels, D.L., and Stern, T.W., 1982, Island-arc, back-arc, and melange terranes of northen Virginia: tectonic, temporal and regional relationships, abstract: Geological Society of America Abstracts with Programs, v. 14, p. 584.

Pavlides, L., 1989, Early composite melange terrane, central Appalachian Piedmont, Virginia and Maryland; its origin and tectonic history: Geological Society of America Special Paper 228, pp. 135-193.

Pazzaglia, F.J, and Gardner,T.W., 1993, Fluvial terraces of the lower Susquehanna River: Geomorphology, v. 8, p. 83-113.

Pazzaglia, F.J., and Gardner, T.W., 1994, Late Cenozoic flexural deformation of the middle U. S. Atlantic passive margin: Journal of Geophysical Research, v. 99, pp. 12-12,157.

Pazzaglia, F.J., Gardner, T.W., and Merritts, D.J., 1998, Bedrock fluvial incision and longitudinal profile development over geologic time scales determined by fluvial terraces: American Geophysical Union, Geophysical monograph 107.

Richardson, K., and Carling, P.A., 2005, A typology of sculpted forms in open bedrock channels: Geological Society of America Special Paper 392, 108 p.

Reusser, L.J., Bierman, P.R., Pavich, M.J., Zen, E.A., Larsen, J., and Finkel, R., 2004, Rapid late Pleistocene incision of Atlantic passive-margin river gorges: Science, v. 305, pp. 499-502.

Schumm, S.A., and Kahn, H.R., 1972, Experimental study of channel patterns: Geological Society of America Bulletin, v. 83, pp. 1755-1770

Schumm, S.A., 1977, The Fluvial System: Wiley and Sons, New York, 340 p.

Selby, M.J., 1985, Earth’s Changing Surface: River Valleys, Clarendon Press; Oxford, p. 264.

Sklar, L., and Dietrich, W.E., 1998, River lomngituindal profiles and bedrock incision models: stream power and the influences of sediment supply

Smith, J.W., Milici, R.C., and Greenberg, S.S., 1964, Geology and mineral resources of Fluvanna County: Virginia Division of Mineral Resources Bulletin 79, 62 p.

Spotila, J.A., Bank, G.C., Reiners, P.W., Naeser, C.W., Naeser, N.B., Henika, B.S.,2004, Origin of the Blue Ridge escarpment along the passive margin of Eastern North America: Basin Research, v. 16 pp. 41-63.

Tooth, S., and McCarthy, T.S, 2003, Anabranching in mixed bedrock-alluvial rivers: the example of the Orange River above Augrabies Falls, Northern Cape Province, South Africa: Geomorphology, v. 57, pp. 235-262.

Tucker, G.E., and Bras, R.L., 2000, A stochastic approach to modeling the role of rainfall variability in drainage basin evolution: Water Resources Research, v. 36, pp. 1953-1964.

Virginia Division of Mineral Resources, 1993, State Geologic Map of Virginia: Virginia Division of Mineral Resources, scale 1: 500,000

Ward, D.J., Spotila, J.A., Hancock, G.S., Galbraith, J.M., 2005, New constraints on the late Cenozoic incision history of the New River, Virginia: Geomorphology, article in press.

Whipple, K. X., 2004, Bedrock Rivers and the Geomorphology of Active Orogens: Annual Review of Earth Planet Science, v. 32, pp. 151-185.

Whipple, K. X., Hancock, G.S., and Anderson, R.S., 2000, River incision into bedrcok: Mechanisms and relative efficay of plucking, abrasion, and cavitation, Geological Society of America Bulletin, v. 112, no. 3, pp. 490-503.

Whipple, K. X. and Tucker, G.E., 1999, Dynamics of the stream-power river incision model: implications for height limits of mountain ranges, landscape response timescales, and research needs: Journal of Geophysical Research, v. 104, pp. 17661-17674.

Wohl, E., Ikeda, H., 1998, Patterns of bedrock channel erosion on the Boso Peninsula, Japan: Journal of Geology, v. 106, p. 331-345.

Zaprowski, B.J., Evenson, E.B., Pazzaglia, F. J., Epstein, J.B., 2001, Knickzone propagation in the Black Hills and northern High Plains: A different perspective on the late Cenozoic exhumation of the Laramide Rocky Mountains, Geology, v. 29, pp. 547-550.

Figures

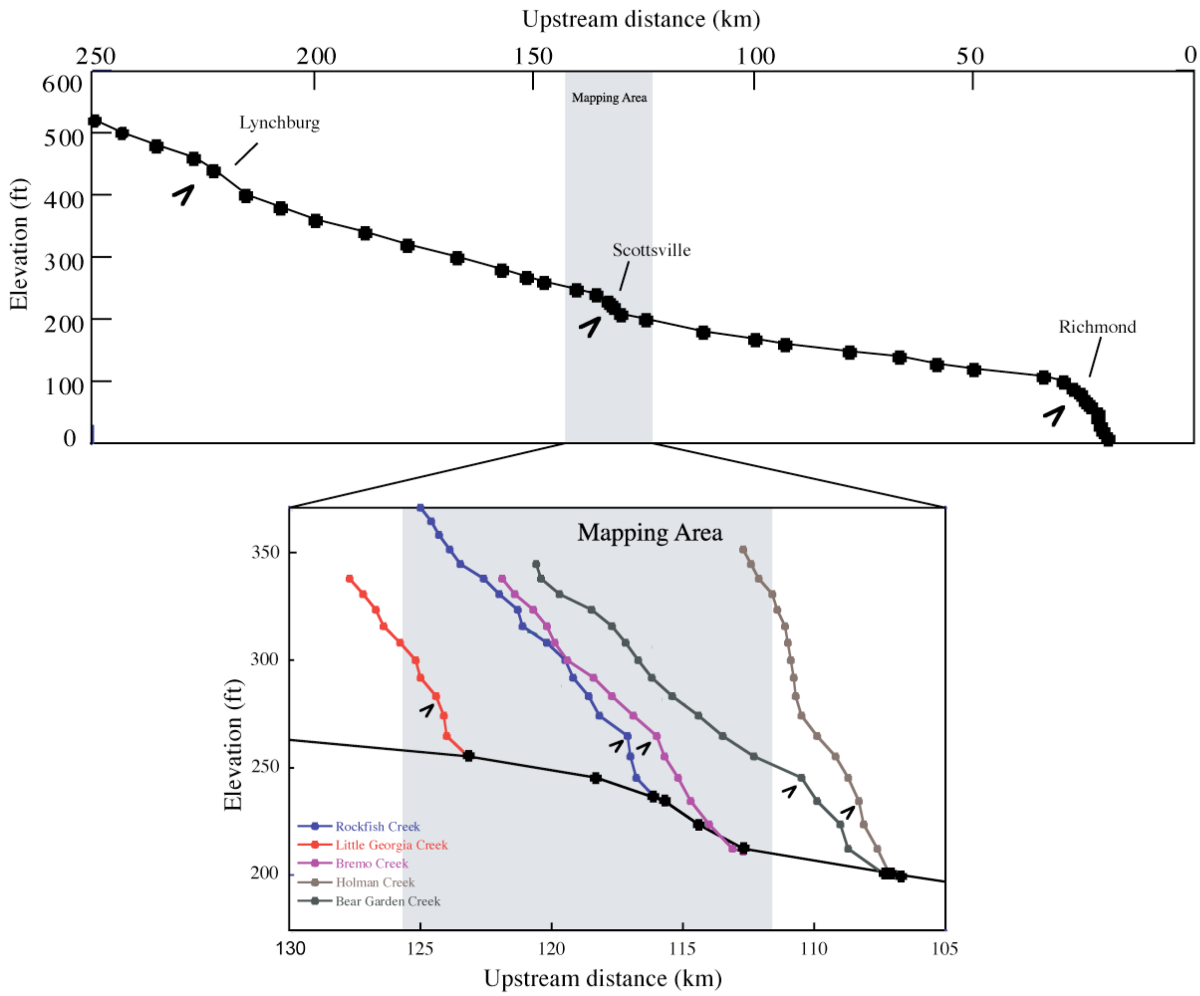


Figure 1. Longitudinal profile of the James River from the Fall zone in Richmond to 250 km upstream. Knickpoints are indicated by arrows. Study area is enlarged below with five additional tributary profiles. Tributaries also show knickzones as indicated by arrows.

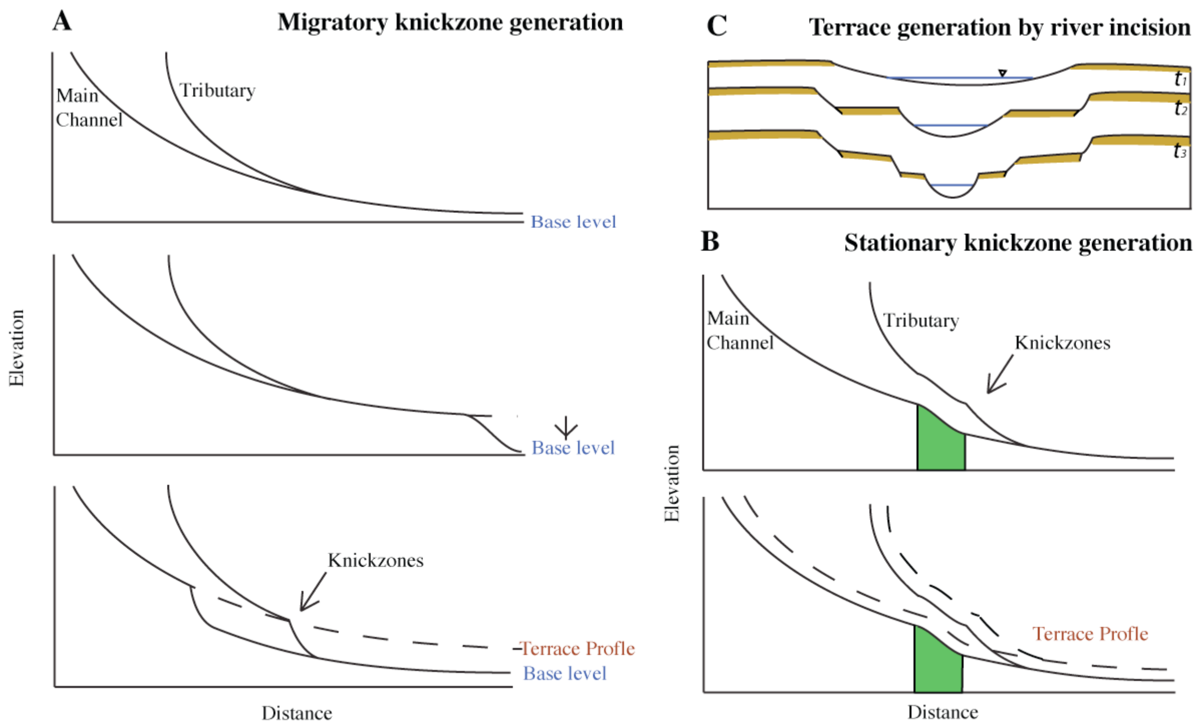


Figure 2. **A** Illustration of migratory knickzone generation by base level fall. Notice that subsequent terrace profiles follow the original longitudinal profile. **B** Stationary knickzone generation by differential lithology. The green area represents a lithologic unit resistive to erosion. Across this reach of the profile, slope must increase if erosion of the whole profile is constant. Note that for stationary knickzones, terrace profiles mimic the present longitudinal profile. **C** Cross sectional view of longitudinal profiles, displaying a time sequencing of strath terrace generation. Channel narrowing is not necessarily a product of incision.

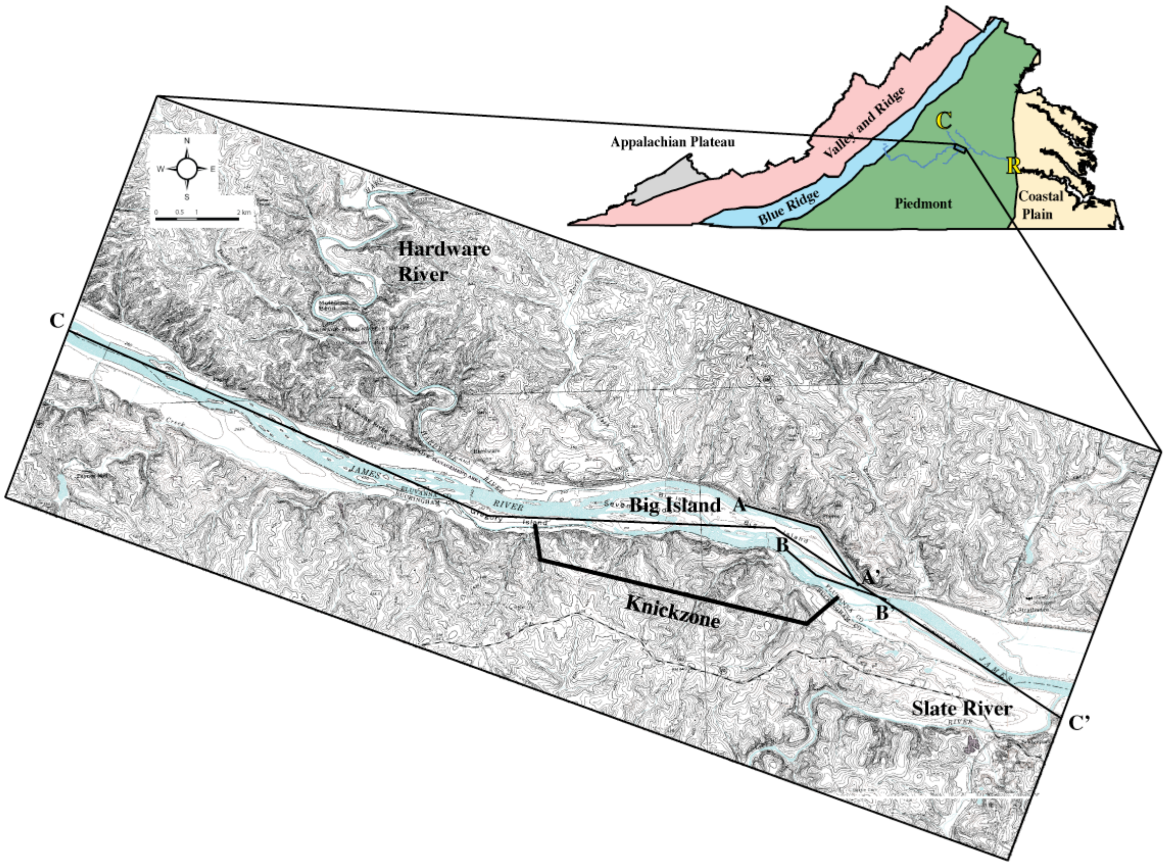


Figure 3. Location of study area along the James River in the Virginia Piedmont. Enlarged topographic map depicts knickzone along an anabranching reach of the river. Three transect lines refer to surveyed longitudinal profiles and cross section in figure 11.

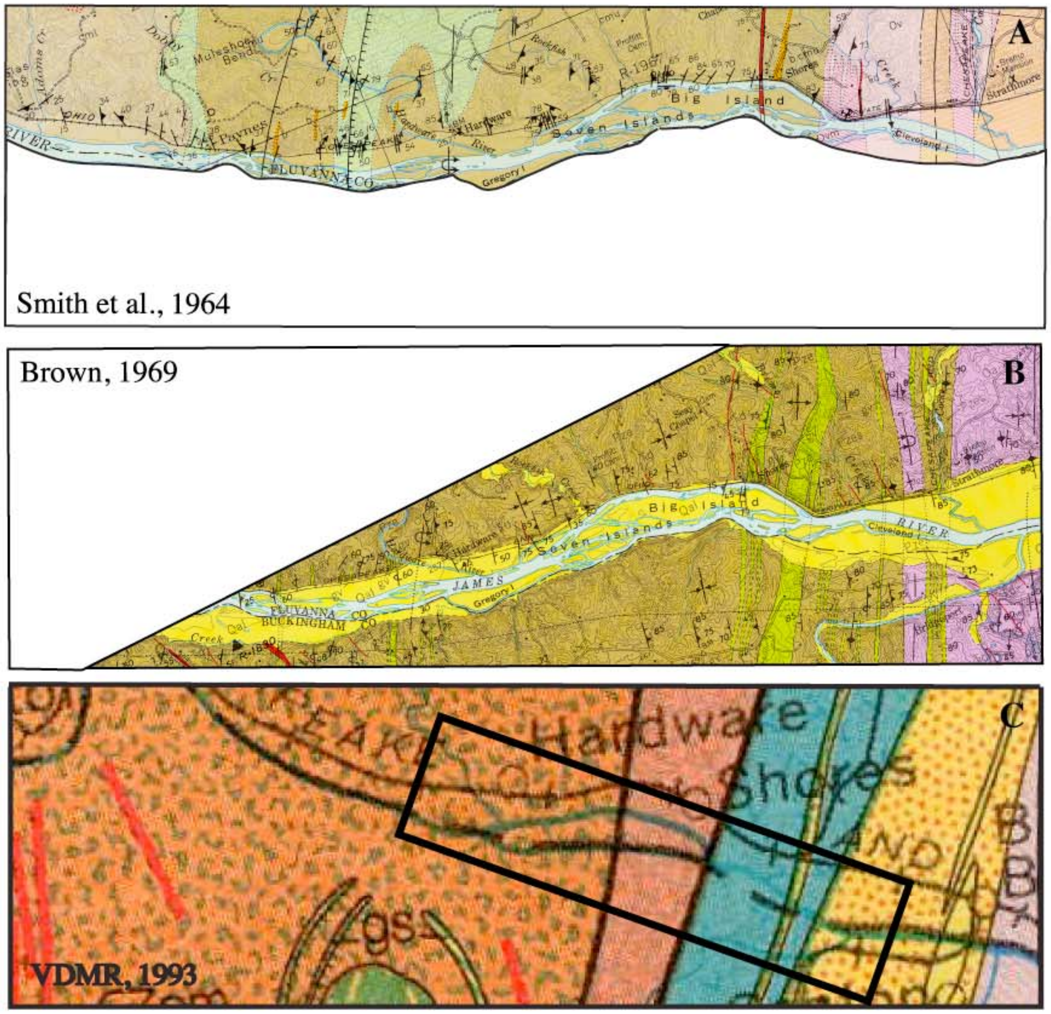


Figure 4. Previous maps of this region created by **A** Smith *et al.* (1964) of the north bank of the James within the study area at 1:62,500 scale, **B** Brown (1969) along the majority of the south bank of the study area at 1:62,500, and **C** VDMR (1993), the Virginia Geologic State Map at 1:500,000 scale (study area is boxed).

Figure 5. Photographs of summer field work. **A** Cobbles in small tributary indicate the presence of an alluvial deposit nearby. **B** Hand auguring of a terrace for soil analysis. **C** Small terrace tread visible in foreground. Woodpile on left is ~1m high. **D** Uncommonly large metagreywacke exposure, fracture plane visible. LP for scale.

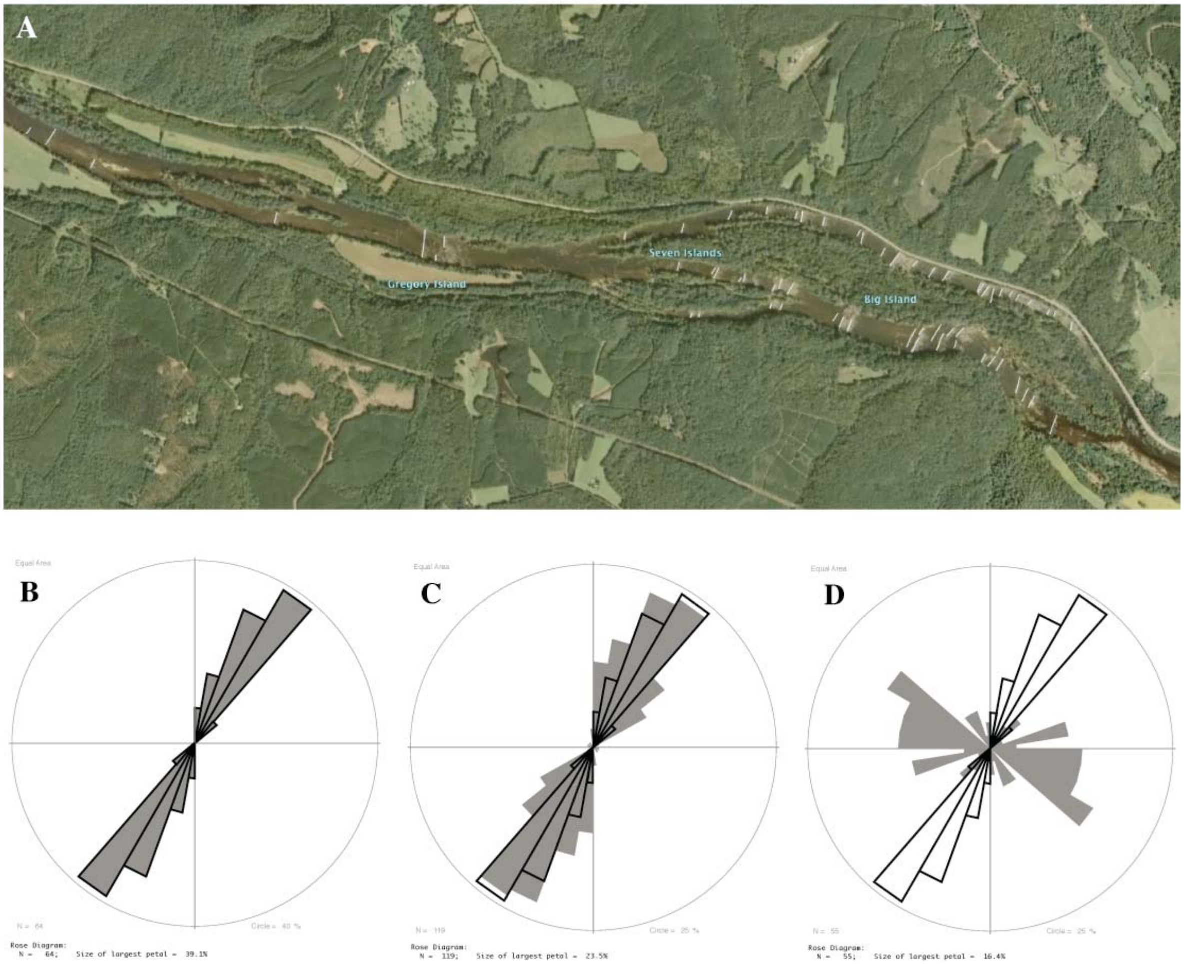


Figure 6. Aerial photo analysis of ribbed outcrops in the main channel. **A** Sample aerial photo with linearized ridges for analysis. **B** Rose diagram of strike along ridge exposures; outer boundary 40% of data. **C** Entire study area foliation data with **A** imposed; outer boundary 25% of data. **D** Entire study area fracture set data with **A** imposed; outer boundary 25% of data.

Figure 7. Bedrock and surficial map of the study area.

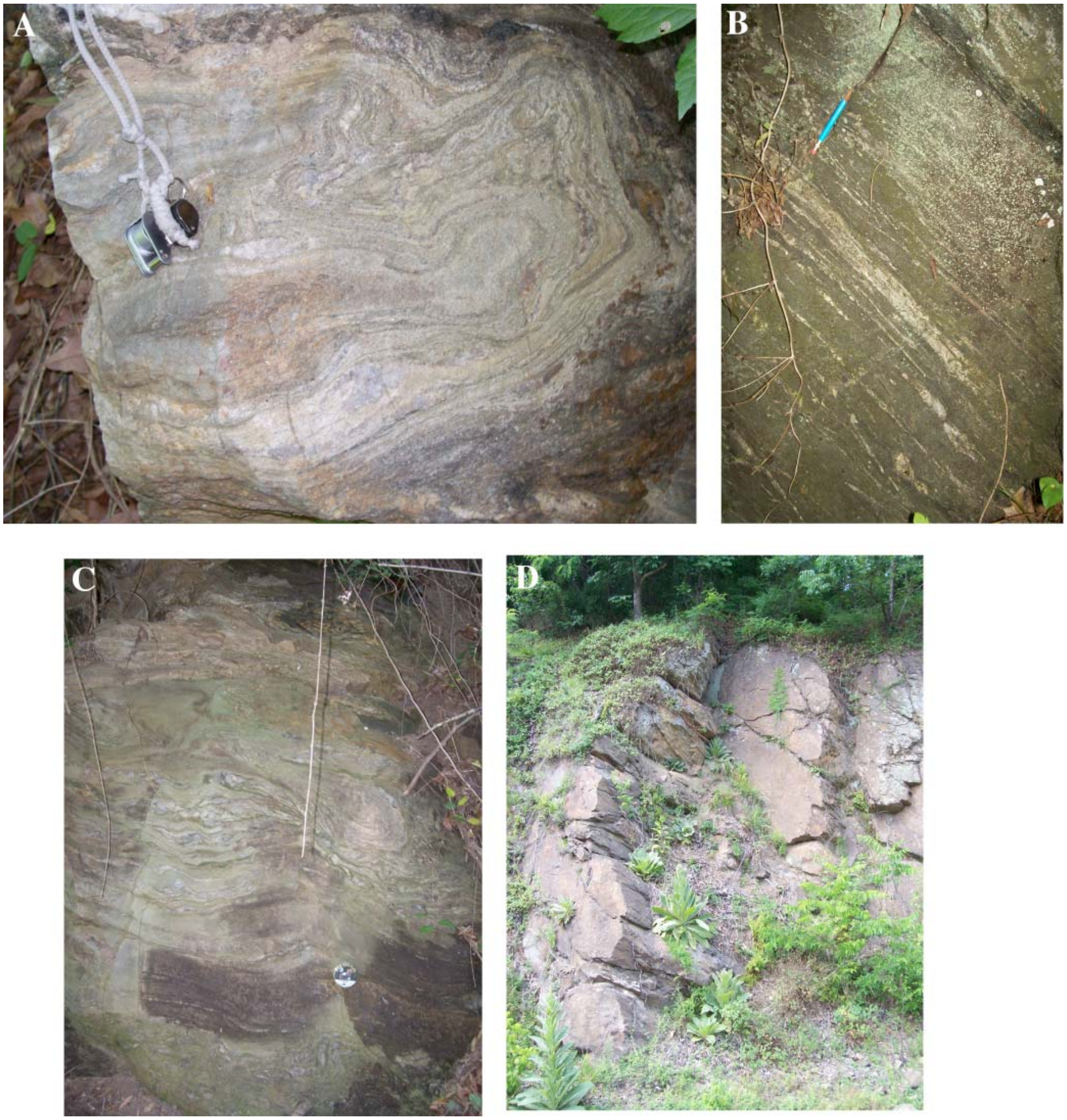


Figure 8. Outcrop photographs comparing western metagreywacke to central mélange units. **A** Close up of greenstone and quartz in mélange. **B** Close up of “pinstriped” metagreywacke showing lineations. **C** Outcrop of complexly deformed mélange exhibiting greenstone blocks in a gneissic fabric. **D** Cliff exposure of metagreywacke along fracture planes, foliation dips steeply to the east (right of photograph, outcrop ~10m tall).

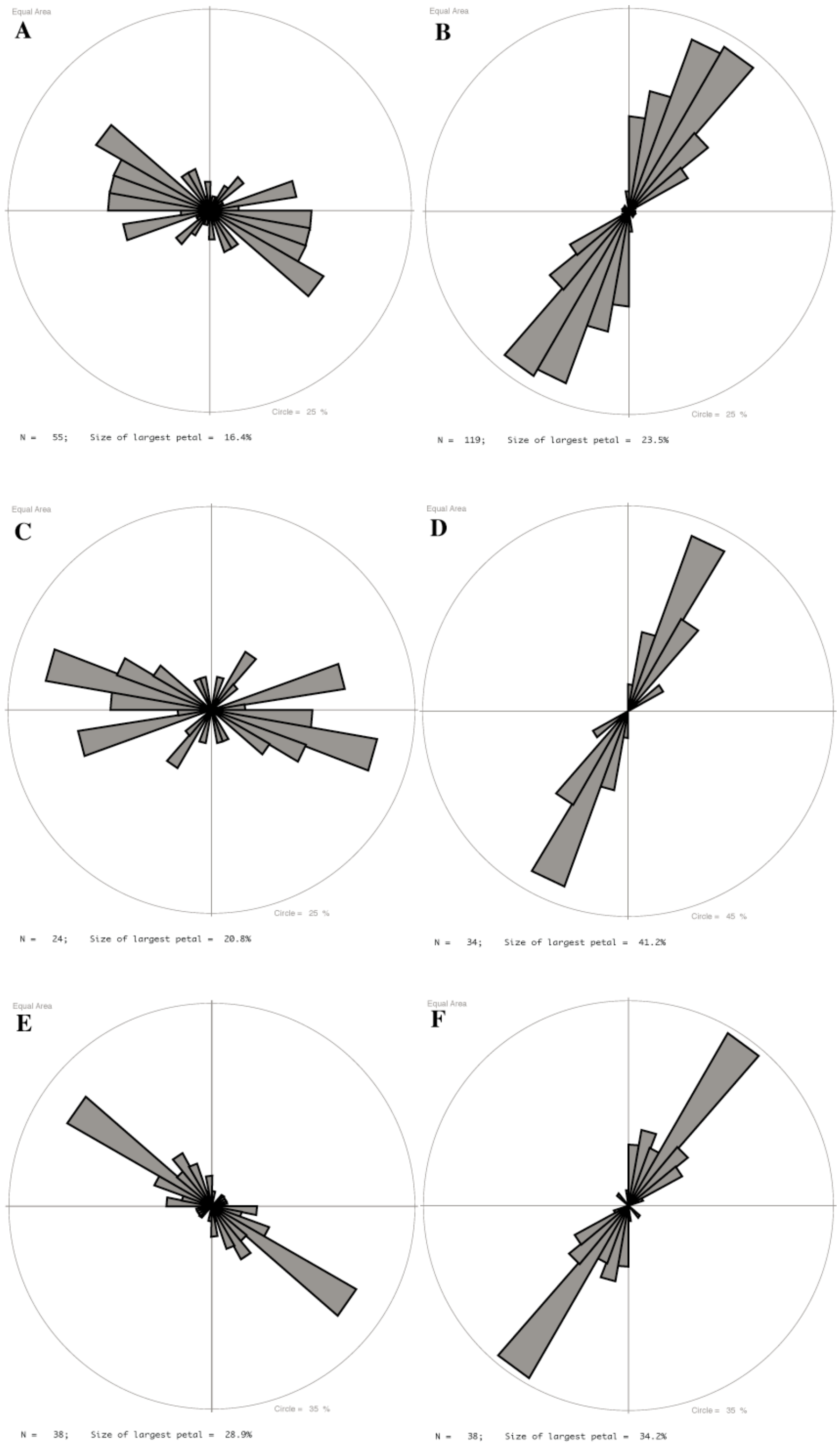


Figure 9. Rose diagrams of area structural patterns. **A** fracture set and, **B** foliation strike patterns for the entire study area. **C** fracture and, **D** foliation patterns for areas just north of the Slate River. **E** fracture and, **F** foliation patterns for areas around the Hardware River.

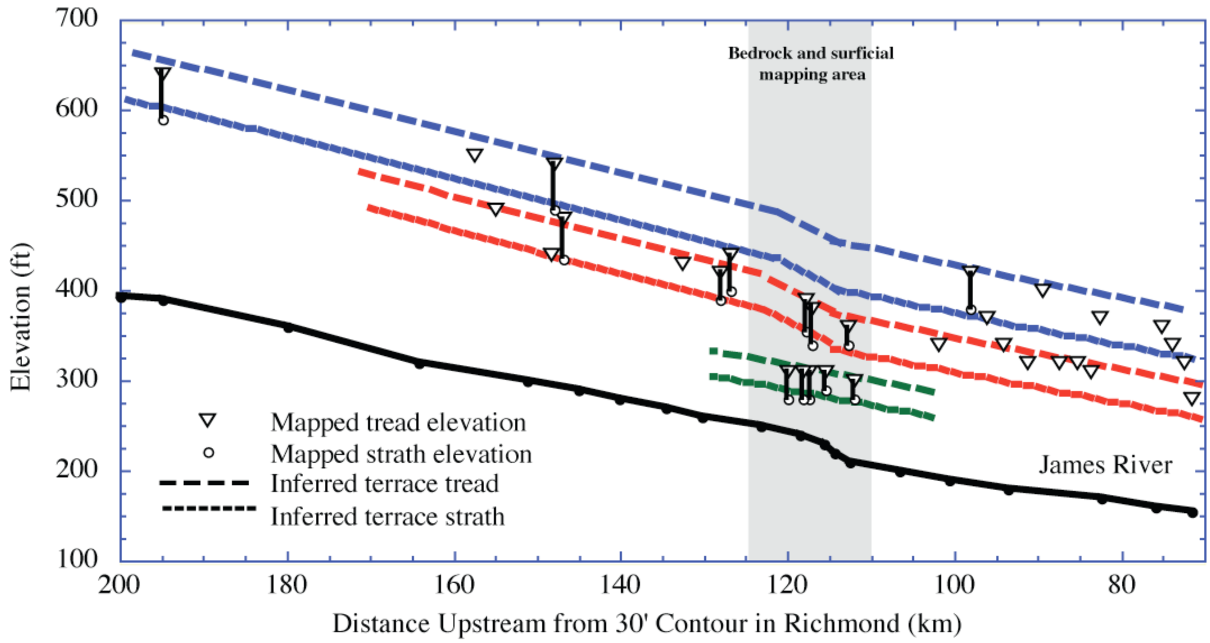


Figure 10. Reconstruction of longitudinal profile from mapped terrace elevations. Strath elevations of five terrace levels within the knickzone have been grouped to represent three profiles. Blue and red profiles are correlated to data outside of the study area collected by Felis (2003) and have been dated to ~1 Ma. Thanks to Lauren Parker for help with figure.

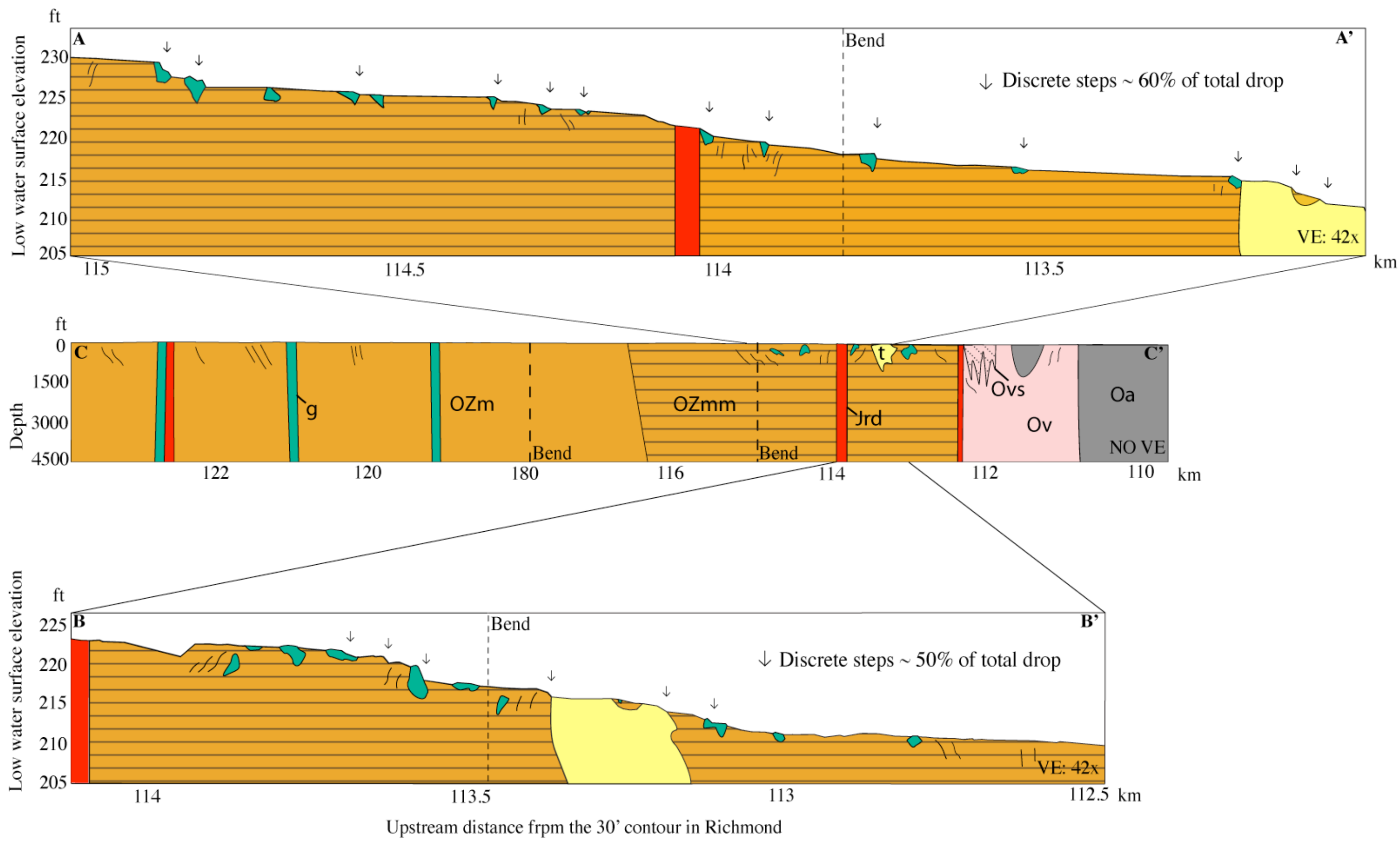


Figure 11. Illustrative cross section in center and surveyed longitudinal profiles above and below. Upper longitudinal profile represents the northernmost transect within the channel. Lower profile represntes the southern transect around Big Island (see transect lines in figure 2). Both profiles represent the lowermost ~2 km of the knickzone. Stepped features in profiled correspond to cross channel ribs that account for 50 to 60 precent of total incision within the toe of the knickzone.

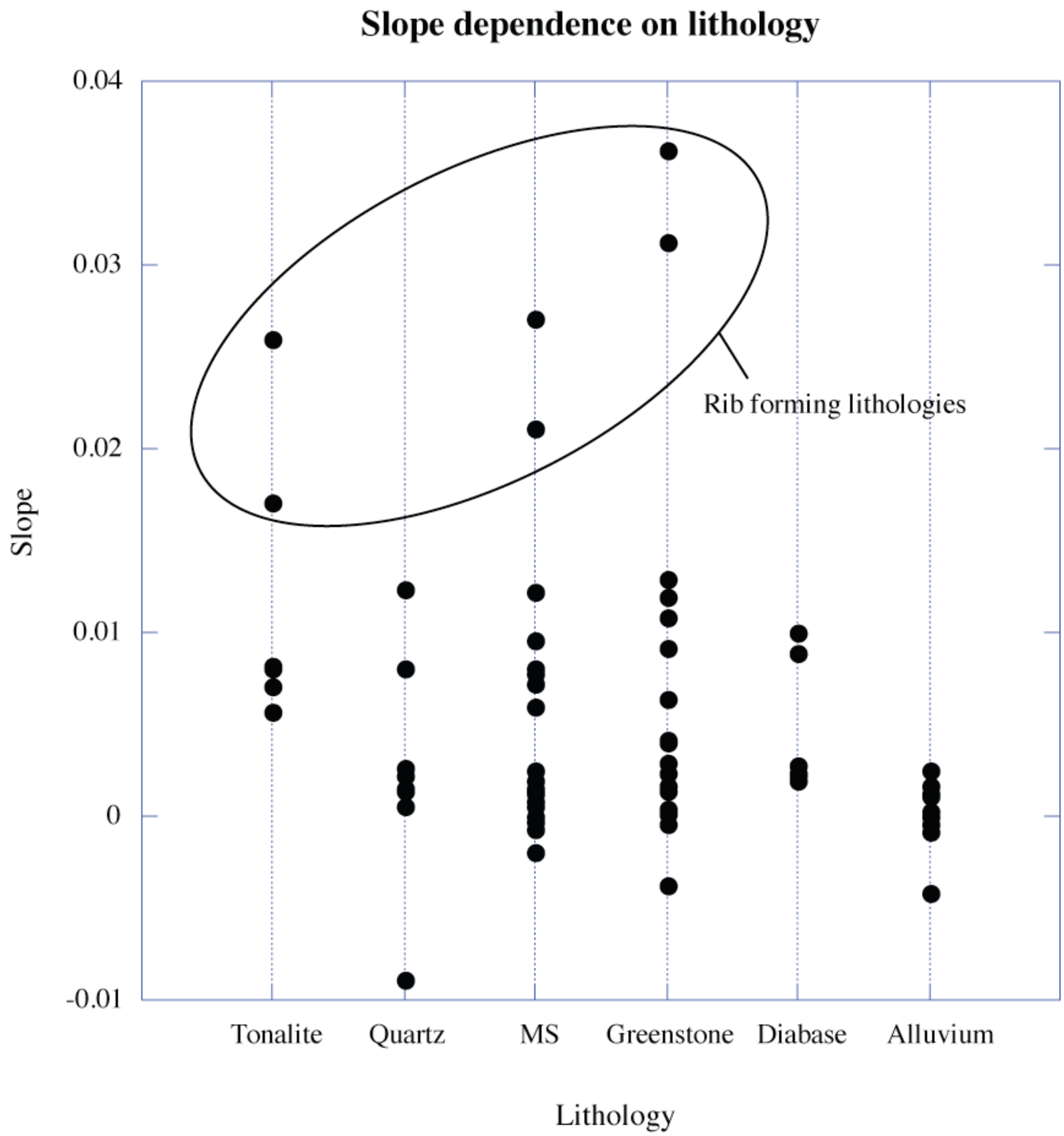


Figure 12. Graph depicting the distribution of straight-line surveyed slopes by bedrock type at that slope location. Data was calculated from the northern survey transect; ~2 km upstream from the base of the knickzone.

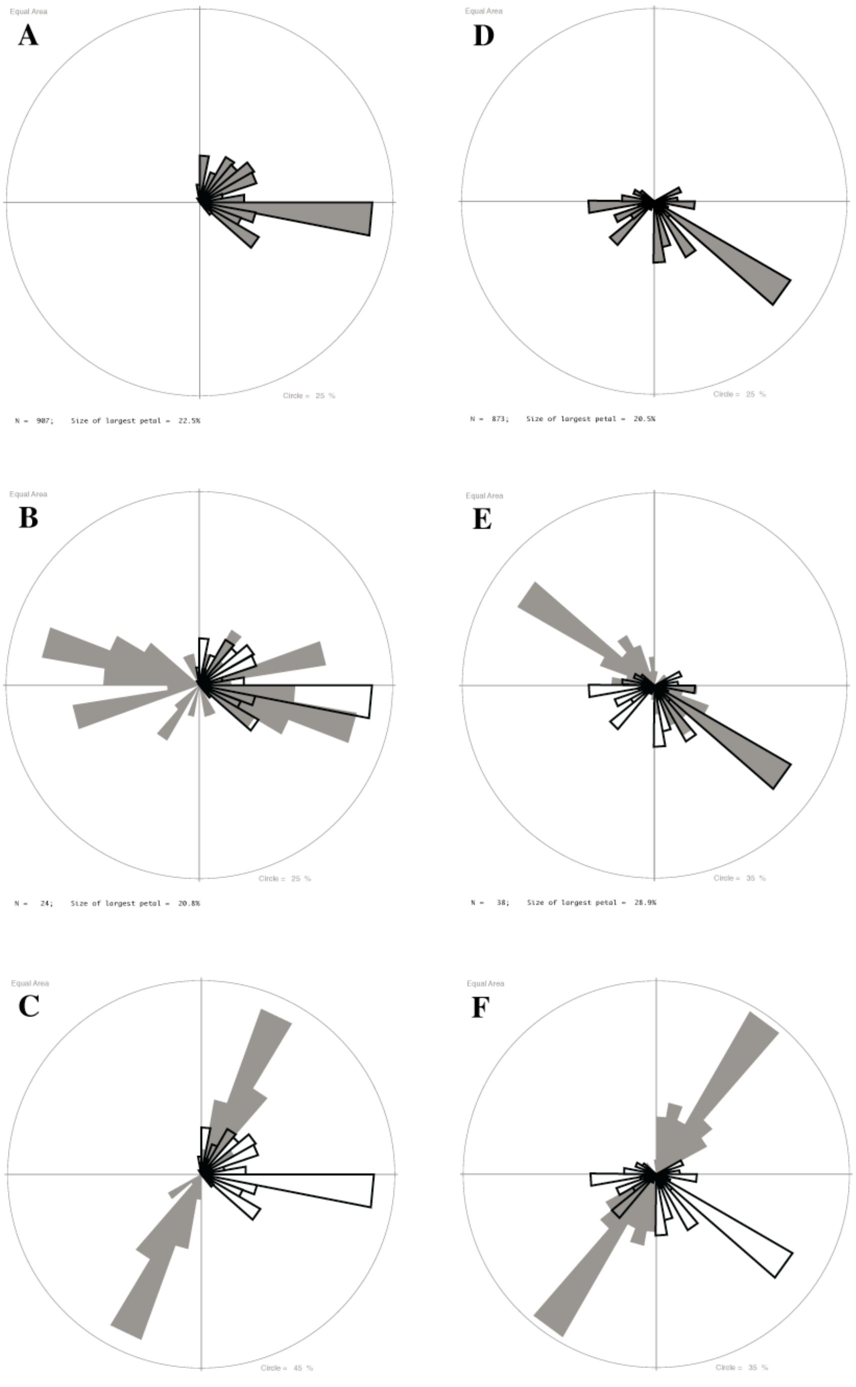


Figure 13. Rose diagram comparison of structural patterns for the Slate (**A**-**C**) and Hardware Rivers (**D**-**F**). **A** linearized flow direction of the Slate River. **B** pattern of fracture strike for area north of the Slate River with **A** superimposed. **C** pattern of foliation strike for area north of Slate River with **A** superimposed. **D** linearized flow direction of the Hardware River. **E** pattern of fracture strike for area around Hardware River with **D** superimposed. **F** pattern of foliation strike for area around Hardware River with **D** superimposed. Circles represent variable amounts of data to lower right of each diagram. Petals represent 10° for all data.

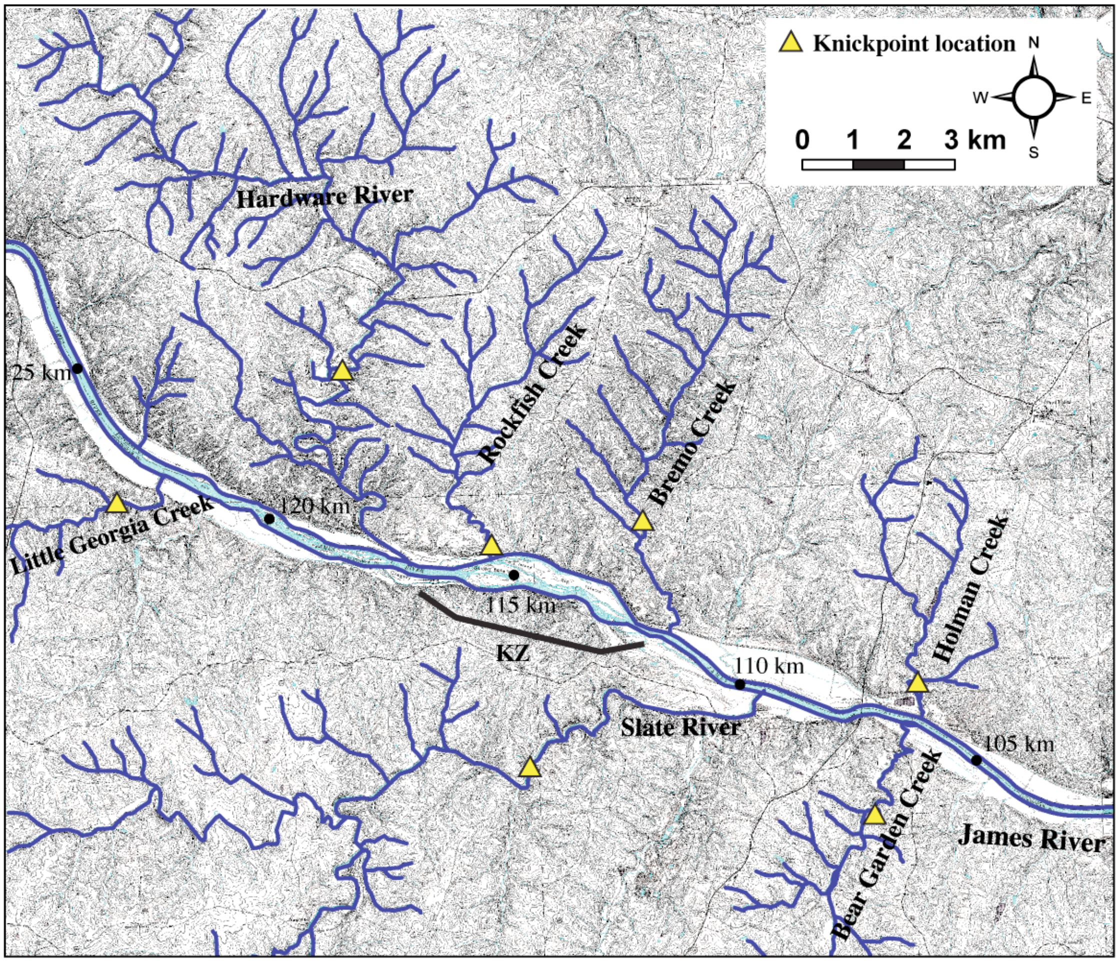


Figure 14. Map of tributary knickpoint locations relative to the James knickzone (KZ). Kilometer markers are upstream from the 30 ft. contour in Richmond. Thanks to Lauren Parker for help with figure.

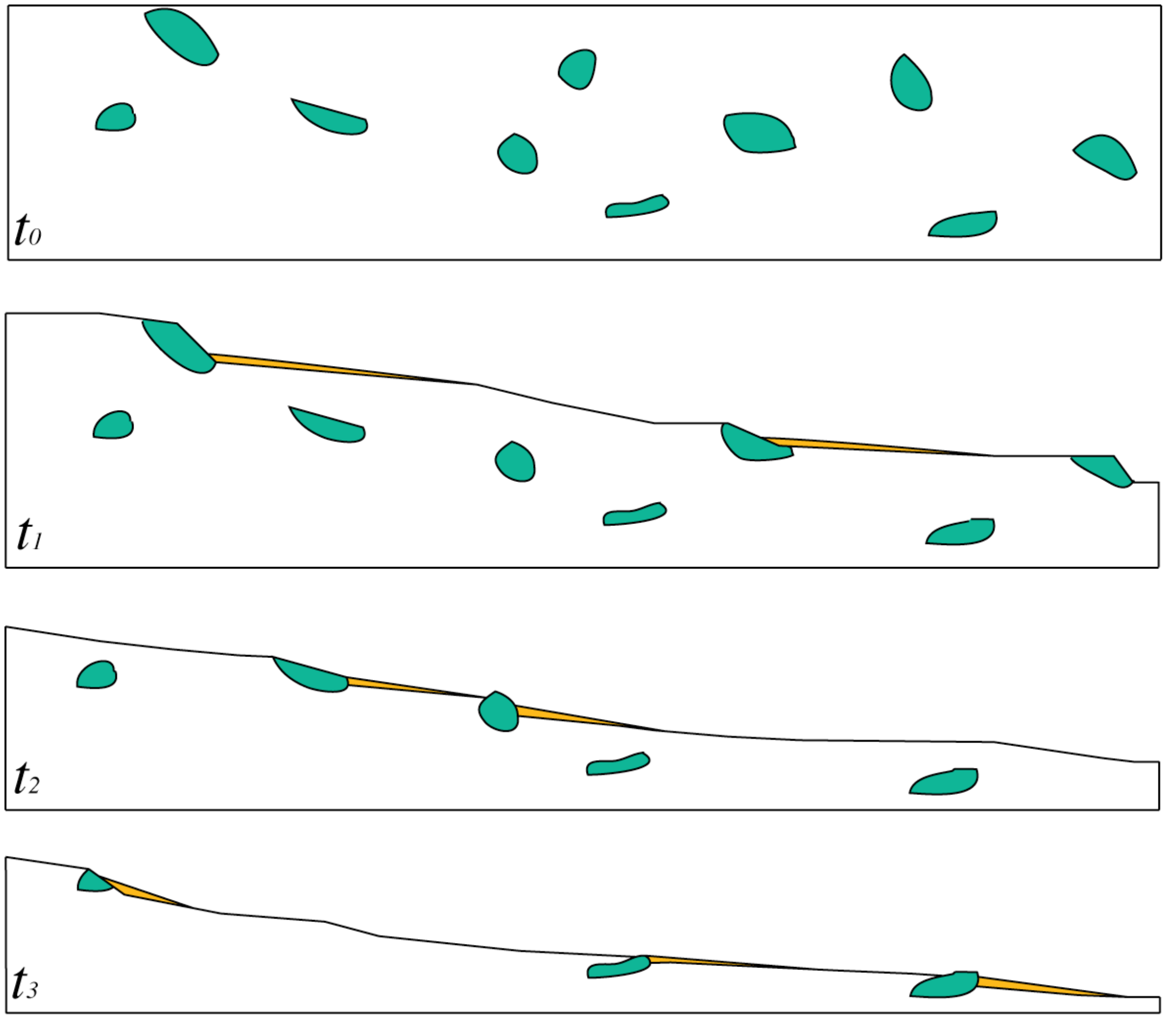


Figure 15. Illustration of differential incision of a lithology with a heterogeneous hardness. Greenstone blocks are harder to erode than metasedimentary matrix leading to the evolution of a stepped profile. Ephemeral alluvial deposition in slack water eddies provides temporary armoring. Modified from Whipple et al. (2000).

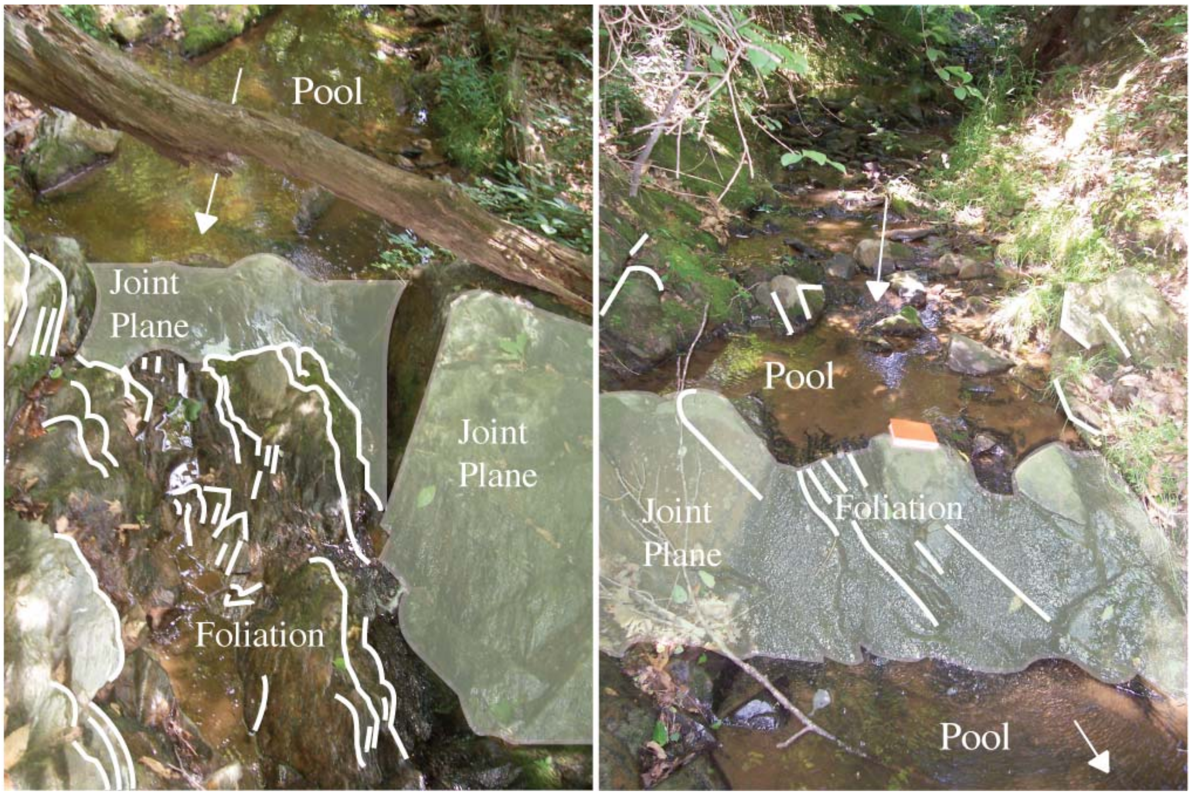


Figure 16. Illustrated photographs of small tributary knickpoints. Flow is to the viewer along arrows and pools above and below the knickpoint. Stream incises parallel to foliation planes here exposed along a fracture plane. Left hand image shows a greatly dissected fracture plane while the right hand image shows an intact fracture plane. Width of both streams are ~1.5 m (note field book for scale in right hand picture)

Appendix A: Thin Section Descriptions

A.
Sample: GH0703074B
UTM: 4178633 N, 732880 E
Unit: Mélange
Mineralogy (approximate %): Chl (45), Musc (23), Carbonate (10), Amphibole (7), Epi (7), Qtz (5), Opaque (5), Bio (3)
Name: Chloritic metasedimentary matrix of mélange
Notes: Micas dominate the rock, relatively low quartz content in groundmass. Opaques likely pyrite, but may be magnetite or hematite; rock not strongly magnetic.
Interpretation: Fine grained mélange matrix showing a slight fabric with minimal mica growth. Strong presence of chlorite, epidote and amphibole indicate presence of greenstone locally. Carbonates inferred to be from metamorphic fluids.

B.
Sample: LP0702075A
UTM: 4178575 N, 733850 E
Unit: Metasediments/Metavolcanics
Mineralogy (approximate %): Qtz (50), Musc (40), Feldspars (10), minor opaques
Name: Quartzose-muscovite porphyroblastic schist
Notes: Quartz and feldspars clastic, but largely recrystalized in groundmass. Porhyroblasts iron oxides, but too highly weathered to determine original mineral, likely pyrite.
Interpretation: Few quartz clasts show mica fish-tail development indicative of shear. Strong mica growth and alignment, and quartz recrystalization from originally clastic matrix.

C.
Sample: KL0630073C
UTM: 4178750 N, 732984 E
Unit: Mélange
Mineralogy (approximate %): Feldspar (Plag) (55), Qtz (30), Epi (10), Musc (5).
Name: Tonalite
Notes: Large plagioclase crystals exhibit albite twinning. Interlocking texture lacking any preferential fabric. Epi inferred to possibly be from metamorphic fluids.
Interpretation: Little recrystalization, shearing, or mica growth indicates largely unmetamorphosed block in mélange matrix. However some plagioclase crystals contain muscovite as sericite, so low grade metamorphism may have occurred (or retrograded higher grade metamorphism). May be intrusion, but more likely a block; lacks evidence of contact metamorphism in outcrop. Interpreted to be a tonalite block in metasedimentary matrix of mélange.

D.
Sample: KL0612073B
UTM: 4180761 N, 726299 E

Unit: Metagreywacke (Greenstone block)
Mineralogy (approximate %): Chl (40), Epi (20), Amph (15), Qtz (10), Carbonate (10), Opaque (5)
Name: Greenstone
Notes: Quartz and carbonate inferred to be from metamorphic fluids. Opaques likely magnetite, may be pyrite or hematite.
Interpretation: Similar to greenstone observed in mélange area, however slightly less metamorphosed with distinctive metagreywacke matrix.

E.
Sample: GH0615072A
UTM: 4179929 N, 731439 E
Unit: Metagreywacke
Mineralogy (approximate %): Chl (40), Musc (30), Qtz (20), Carbonate (10), Bio minor
Name: Schistose metagreywacke
Notes: Quartz is entirely recrystalized occurring in bands between elongated micas
Interpretation: Micas aligned in a strong schistose fabric, yet still relatively fine grained. Indicative of a high level of deformation, but perhaps not metamorphism (as micas would have grown larger).

F.
Sample: LP0916074A
UTM: 4180504 N, 724419 E
Unit: Metagreywacke
Mineralogy (approximate %): Chl (50), Qtz (30), Musc (15), Carbonate (5), Bio minor, minor Opaques
Name: "Pinstriped" quartzose metagreywacke
Notes: Quartz recrystalized. High mica content, but very fine grained, often difficult to differentiate minerals. Photographed slide unpolished.
Interpretation: Opaques lineated with general fabric. Micas small, and little evidence of overgrowth. This lithology is a finer grained quartzose variety of the metagreywacke unit, it is generally less deformed and, likely, less metamorphosed as well.

G.
Sample: KL0615071A
UTM: 4179947 N, 731282 E
Unit: Metagreywacke
Mineralogy (approximate %): Qtz (30), Musc (30), Chl (30), Opaque (10), Carbonate minor
Name: Muscovite-chlorite schist
Notes: Very large mica grains, many of which have sericitized. Quartz is recrystalized. Opaques euhedral rectangles, likely pyrite but may be an iron oxide. Photographed slide unpolished.
Interpretation: This rock has experienced a higher degree of metamorphism, evidenced through larger mica grains, completely recrystalized quartz, and large euhedral opaques. Mineral assemblage is still similar to the metagreywackes surrounding it, indicative of a

localized area of higher metamorphism, perhaps associated with a larger fluid in put during metamorphism (explaining the carbonates and perhaps the opaques as well).

H.
Sample: KL0612071A
UTM: 4181010 N, 726692 E
Unit: Metagreywacke
Mineralogy (approximate %): Qtz (40), Chl (20), Musc (10), Bio (10), Carbonate (10) Opaque (10)
Name: Quartzose Metagreywacke
Notes: Fine grained; opaques lineated with fabric as in “pinstriped” fashion. Photographed slide unpolished.
Interpretation: Finer grained, with little mica growth indicates a lesser degree of metamorphism and slight fabric indicates a lesser degree of deformation as well.

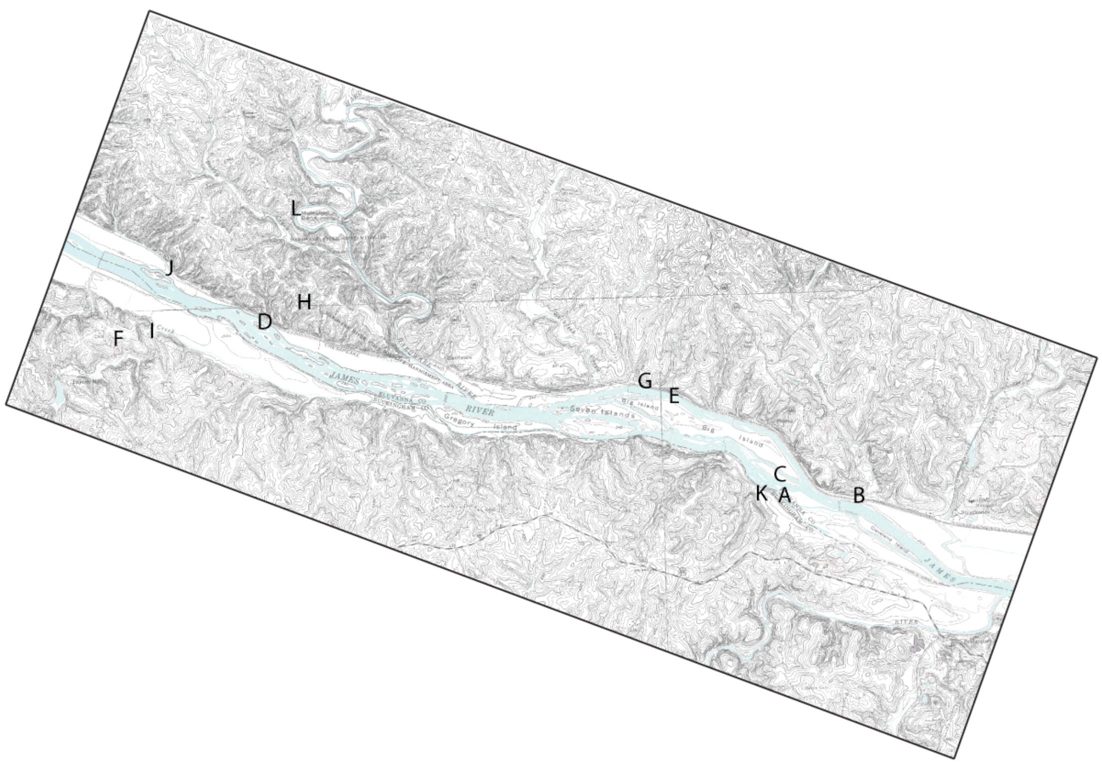
I.
Sample: KL0916073A
UTM: 4180668 N, 724751 E
Unit: Metagreywacke
Mineralogy (approximate %): Qtz (30), Chl (20), Musc (15), Bio (15), Feldspar (10), Opaque (10).
Name: Quartzose metagreywacke
Notes: Euhedral square opaque grains, likely pyrite. Some feldspar shows albite twinning. Photographed slide unpolished
Interpretation: Slight fabric, many grains retain clastic appearance. Opaques crosscut fabric; likely a metamorphic accessory mineral. Metagreywacke only slightly deformed, and lightly metamorphosed.

J.
Sample: KL0612074C
UTM: 4181503 N, 724940 E
Unit: Metagreywacke
Mineralogy (approximate %): Qtz (40), Chl (20), Feldspar (Plagioclase 20, minor Potassic) minor sphene, Bio (10), Carbonate (10)
Name: Quartzose metagreywacke
Notes: Some quartz appears to be sericitized, and most is recrystalized. Most feldspars show albite twinning. Slightly larger grains, some appear to be clastic, particularly feldspars.
Interpretation: Slight fabric, some grains still appear clastic, and presence of feldspars all indicate this is a lightly metamorphosed metagreywacke.

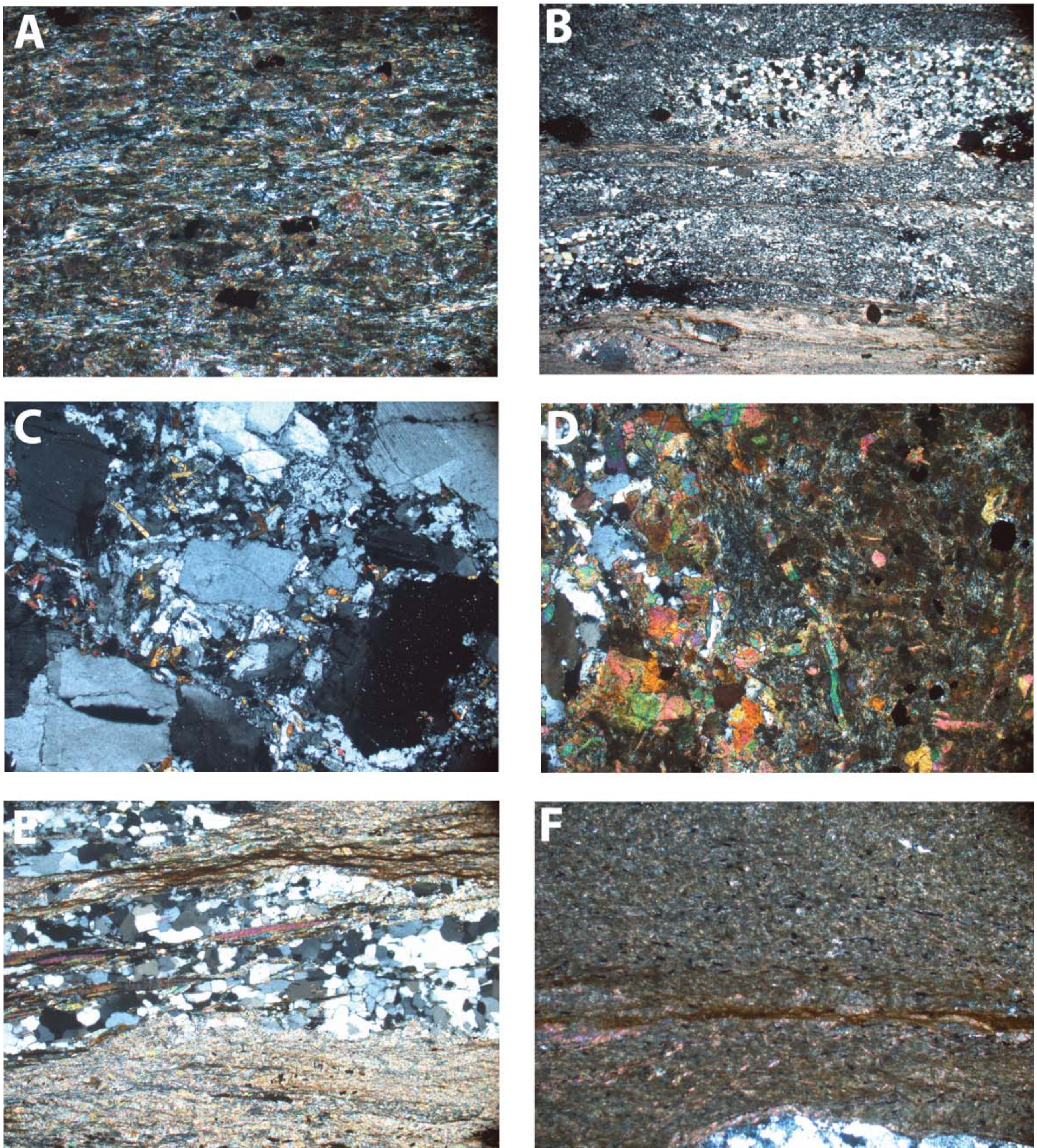
K.
Sample: KL0701073A
UTM: 4178595 N, 732719 E
Unit: Mélange
Mineralogy (approximate %): Qtz (30), Carbonate (30), Chl (20), Epi (15), Amph (5)

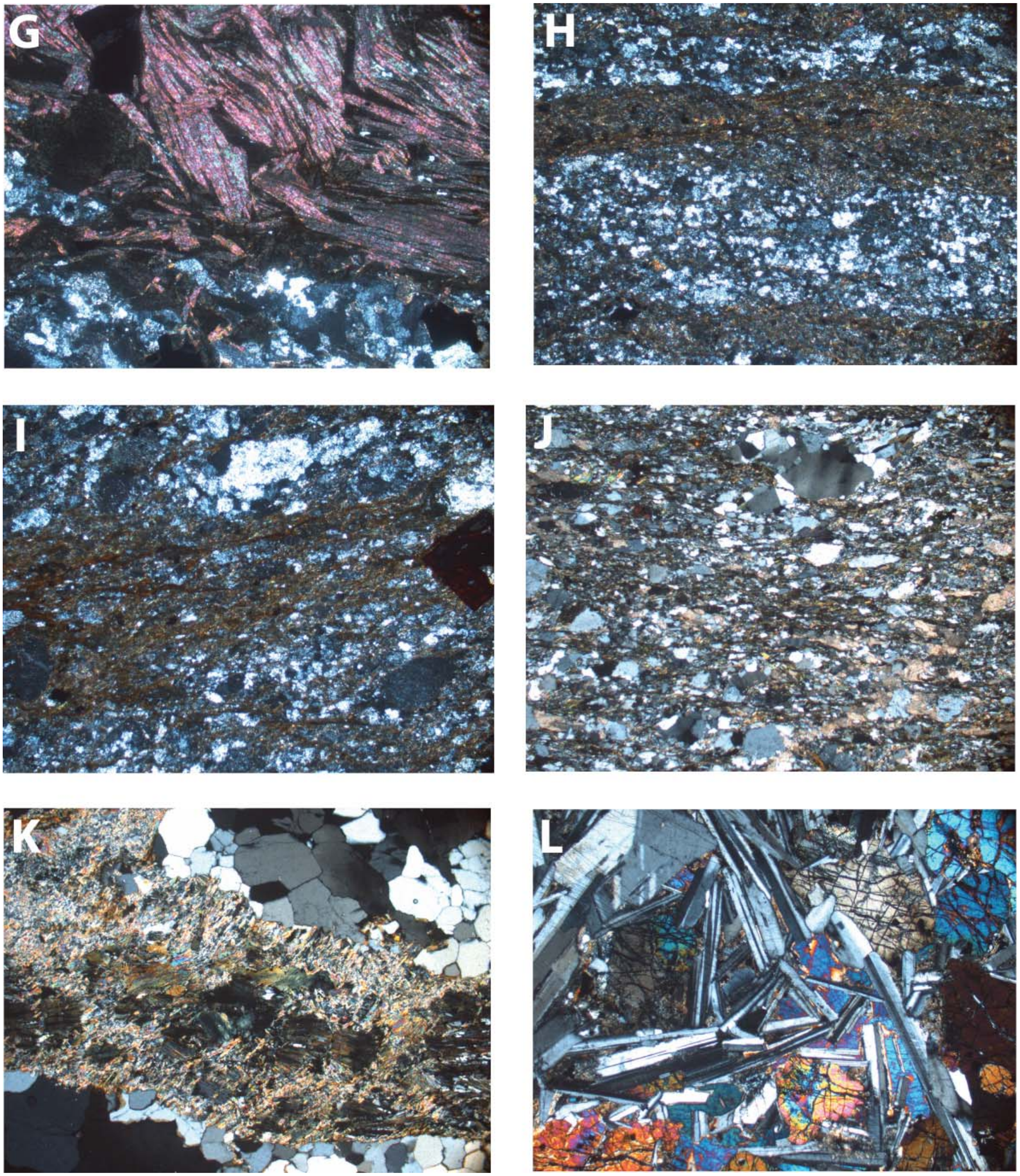
Name: Greenstone
Notes: Quartz is all recrystalized, well developed medium grains of chlorite, finer grained interlocking carbonate, likely calcite.
Interpretation: High quartz and carbonate presence likely due to metamorphic fluid alteration during metamorphism. Rock has experienced a higher degree of metamorphism in comparison to rocks westward.

L.
Sample: KL0613077A
UTM: 4182209 N, 726597 E
Unit: Diabase
Mineralogy (approximate %): Feldspar (Plagioclase) (40), Cpx (35), Ol (15), Opx (10)
Name: Diabase
Notes: Medium grained. Elongate plagioclase grains show Albite twinning. Good cleavage in pyroxene.
Interpretation: Ophitic texture, shows no signs of alteration or weathering. Likely part of a dike.



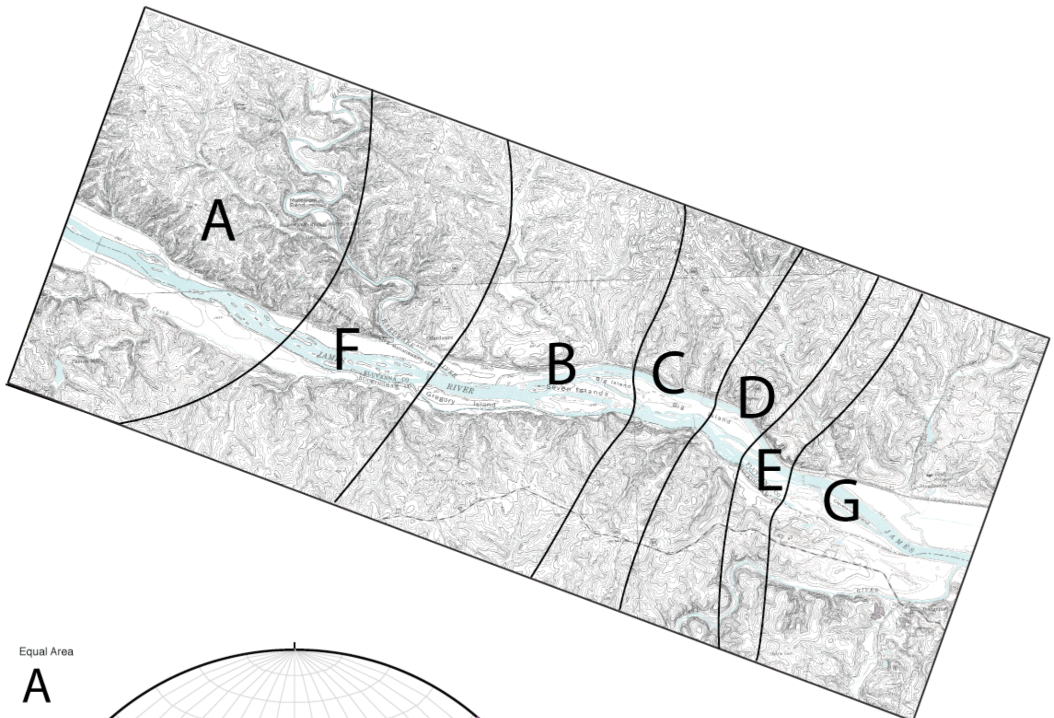
Inset: Location map for thin section photographs
Note all photomicrographs have crossed polars, 50x width of view is 2 mm

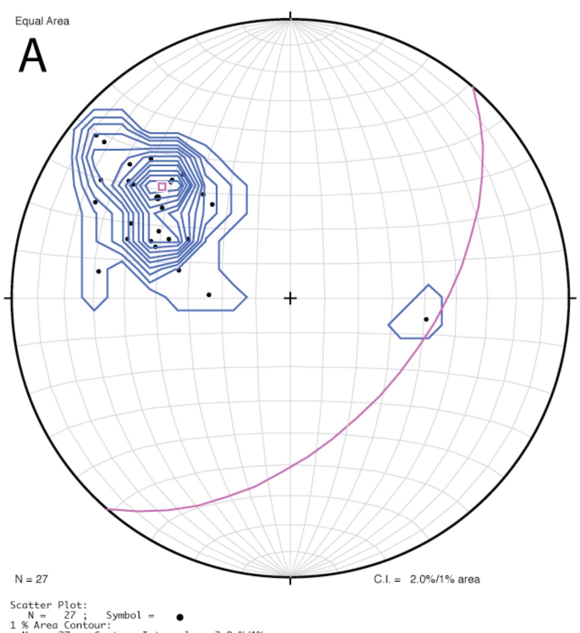

A
B
C
D
E
F

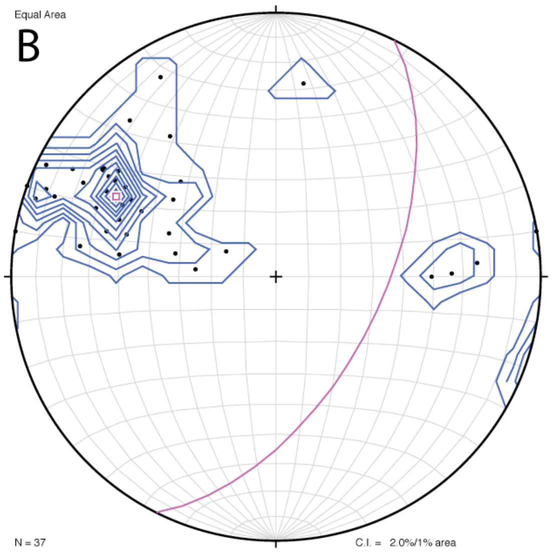

G
H
I
J
K
L

Appendix B: Stereonet Analysis

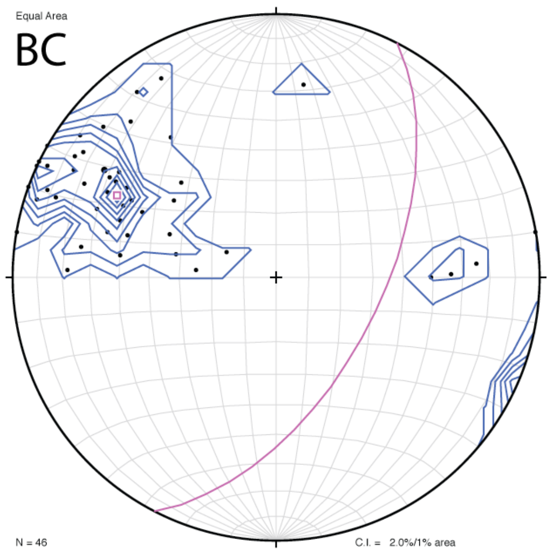
Location map representing spatial data source of stereonets used for structural analysis. Stereonets has 1% countour of poles to foliation. **A** is representative of all data within area **A** on the location map.



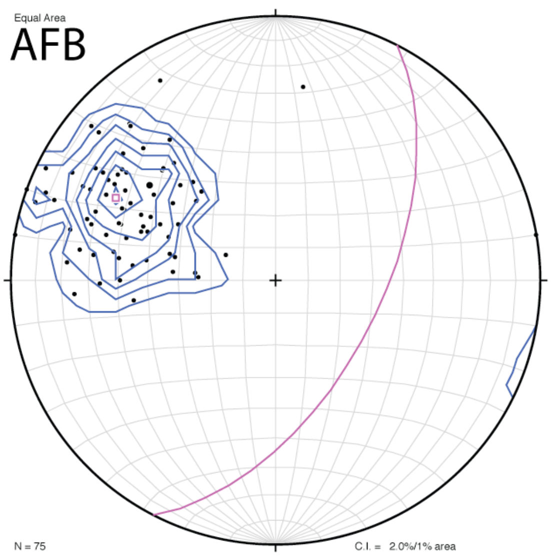




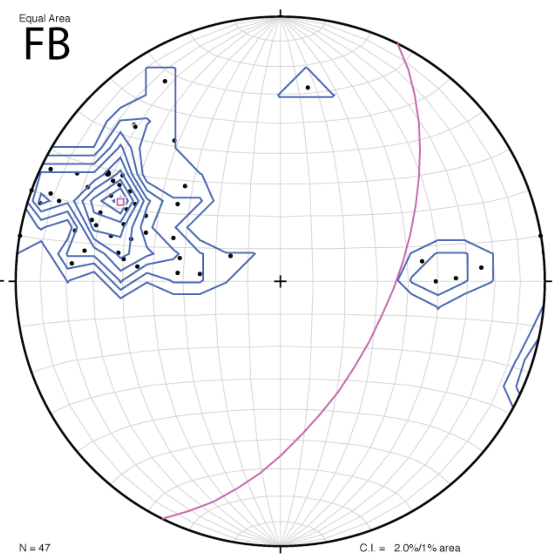

```
Scatter Plot:
   N =   37 ;   Symbol =   ●
1 % Area Contour:
   N =   37;   Contour Interval =  2.0 %/1% area
Pick Great Circle:
   Strike & Dip =  26.7°,  57.1°  E
```



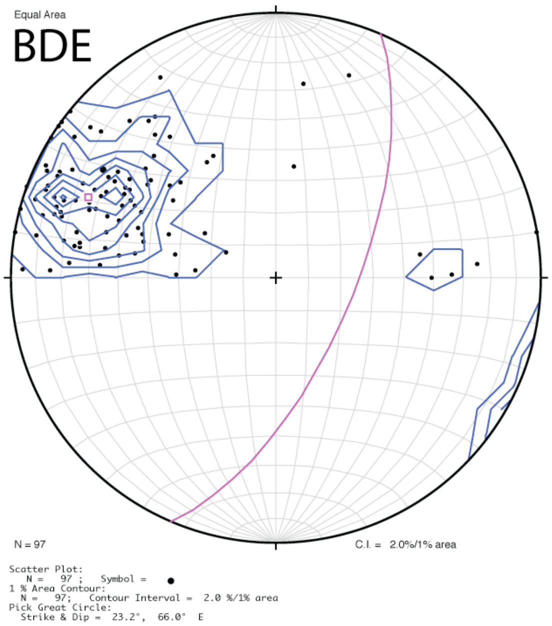

```
Scatter Plot:
   N =   46 ;   Symbol =   ●
1 % Area Contour:
   N =   46;   Contour Interval =  2.0 %/1% area
Pick Great Circle:
   Strike & Dip =  27.3°,  57.5°  E
```

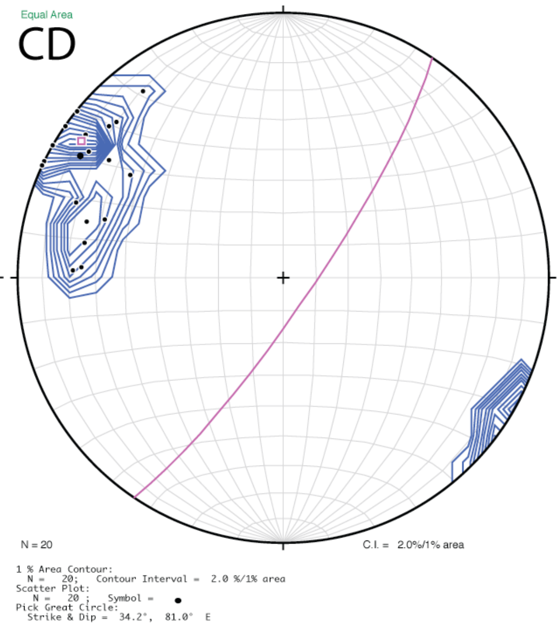


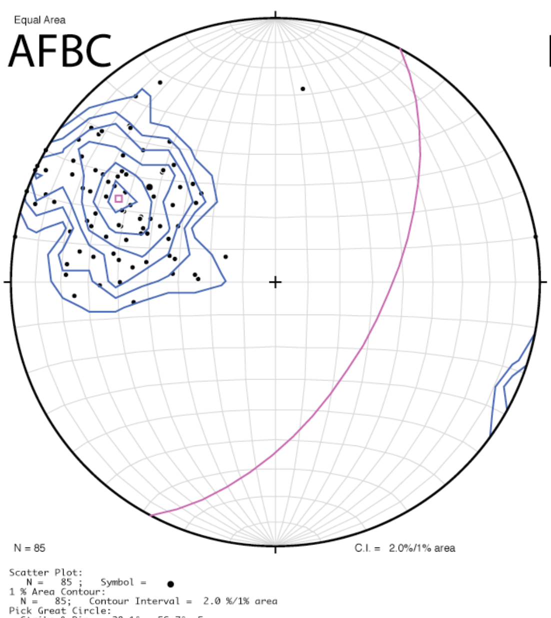

```
Scatter Plot:
   N =   75 ;   Symbol =   ●
1 % Area Contour:
   N =   75;   Contour Interval =  2.0 %/1% area
Pick Great Circle:
   Strike & Dip =  27.3°,  57.5°  E
```

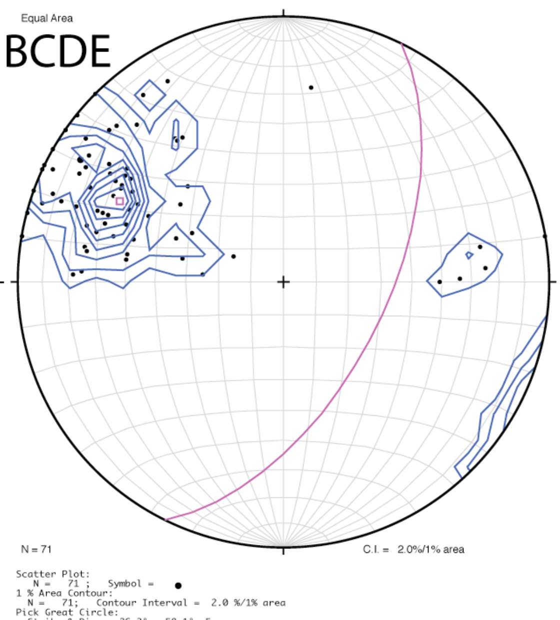


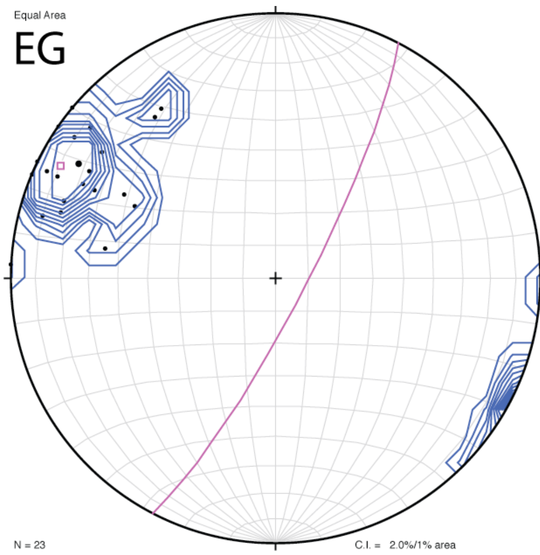

```
Scatter Plot:
   N =   47 ;   Symbol =   ●
1 % Area Contour:
   N =   47;   Contour Interval =  2.0 %/1% area
Pick Great Circle:
   Strike & Dip =  26.4°,  57.0°  E
```


Equal Area
BDE
N = 97
C.I. = 2.0%/1% area
Scatter Plot:
N = 97 ; Symbol = ●
1 % Area Contour:
N = 97; Contour Interval = 2.0 %/1% area
Pick Great Circle:
Strike & Dip = 23.2°, 66.0° E

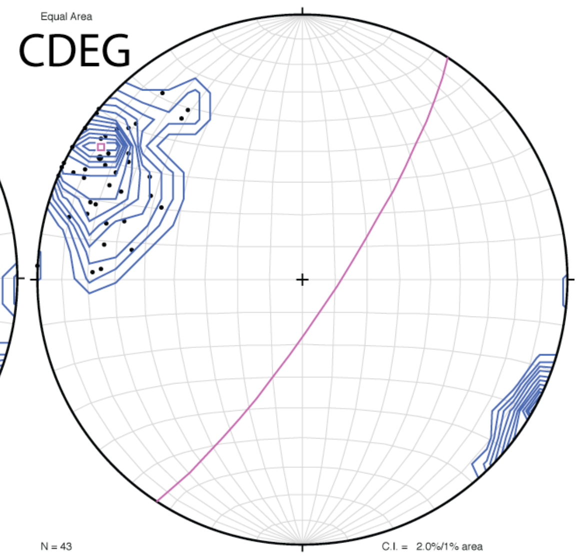

Equal Area
CD
N = 20
C.I. = 2.0%/1% area
1 % Area Contour:
N = 20; Contour Interval = 2.0 %/1% area
Scatter Plot:
N = 20 ; Symbol = ●
Pick Great Circle:
Strike & Dip = 34.2°, 81.0° E


Equal Area
AFBC
N = 85
C.I. = 2.0%/1% area
Scatter Plot:
N = 85 ; Symbol = ●
1 % Area Contour:
N = 85; Contour Interval = 2.0 %/1% area
Pick Great Circle:
Strike & Dip = 28.1°, 56.7° E

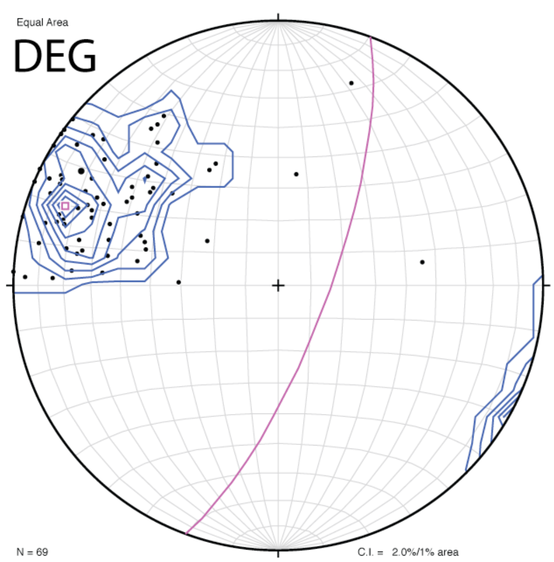

Equal Area
BCDE
N = 71
C.I. = 2.0%/1% area
Scatter Plot:
N = 71 ; Symbol = ●
1 % Area Contour:
N = 71; Contour Interval = 2.0 %/1% area
Pick Great Circle:
Strike & Dip = 26.3°, 58.1° E



Scatter Plot:
N = 23 ; Symbol = ●
1 % Area Contour:
N = 23; Contour Interval = 2.0 %/1% area
Pick Great Circle:
Strike & Dip = 27.6°, 80.7° E



Scatter Plot:
N = 43 ; Symbol = ●
1 % Area Contour:
N = 43; Contour Interval = 2.0 %/1% area
Pick Great Circle:
Strike & Dip = 33.3°, 80.1° E



Scatter Plot:
N = 69 ; Symbol = ●
1 % Area Contour:
N = 69; Contour Interval = 2.0 %/1% area
Pick Great Circle:
Strike & Dip = 20.5°, 74.7° E